THERMAL EFFECTS ON A

ROTATING MISSILE

THESIS

David H. Kristensen
Captain, USAF

AFIT/GNE/ENP/86M-9

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OCT 16 1986

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DEPARTMENT OF THE AIR FORCE

AIR UNIVERSITY

AIR FORCE INSTITUTE OF TECHNOLOGY

Wright-Patterson Air Force Base, Ohio

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Presented to the Faculty of the School of Engineering

of the Air Force Institute of Technology

Air University

In Partial Fulfillment of the

Requirements for the Degree of

Master of Science in Nuclear Engineering

David H. Kristensen, B.S.

Captain, USAF

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Preface

I would like to thank my advisor, Maj. John. F. Prince, Assistant Professor of Physics, Air Force Institute of Technology, for proposing this thesis topic and for his instruction, guidance, and encouragement during months spent working on this project. I'd also like to thank my classmates for their help in solving problems, writing computer code, and proofreading the manuscript. Finally, I'd like to thank my wife Elaine. She was my typist, problem solver, time manager, and expert organizer. She quietly allowed me weeks with the computer, but never permitted me to lose my perspective, or my patience. Without her help, I would not have completed this study. Thanks, I owe you.

- David H. Kristensen

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List of Symbols

CF	correction factor
CT	thermal energy emitted from burst
C_p	specific heat capacity (J/kg-K)
d	missile skin thickness (m)
DGZ	designated ground zero
drd	down-range-distance
$F_{incident}$	radiant exposure from a burst (J/m^2)
GR	ground range (m)
h	heat transfer coefficient (J/m^2-s-K)
I_{ss}	sure-safe intensity
I_{sk}	sure-kill intensity
j	time step
k	thermal conductivity (J/m-s-K)
k	burst #
lt	launch time (s)
MaxT	maximum temperature (K)
P_d	probability of damage
P_s	probability of survival
Q	thermal fluence incident on the missile skin during time step j (J/m^2)
SR	slant range

t	time after a burst (s)
t'	normalized time t/t_{max}
tbl	time of first burst (s)
t_{max}	time after second thermal maximum (s)
T_1, T_2	skin temperature at beginning and end of time step j (K)
T_{air}	ambient air temperature (K)
tf	thermal fraction
W	yield in megatons
Y	yield in kilotons

Abstract

Survivability studies have shown that intercontinental ballistic missiles are vulnerable to thermal effects. In particular, the cumulative thermal effect from a multiburst attack, and laser thermal energy can seriously damage or destroy a missile. One possible defense against the thermal threat is rotation of the missile. The purpose of this thesis was to determine if rotation decreased the maximum skin temperature of the missile increasing the missile's probability of survival.

The study investigated several different scenarios. The first scenario was the Peacekeeper Dense Pack missile system. The missile field was subjected to a walk attack of 2 MT weapons, with the incoming RV's exploding every two seconds. The second scenario was a 4-on-1 attack of a missile launching system. More specifically, one missile was subjected to four bursts located in various positions surrounding the missile. The intent was to determine if rotating a missile, even when surrounded by thermal radiation, would increase the probability of survival. Finally, the missile is attacked by a space-based laser with a maximum absolute

power of 10 megawatts. In all cases, the rotation rate was limited to a maximum of 1.6 radians/second, as established by studies at the Air Force Institue of Technology. Using computer programs, the maximum skin temperature was calculated, with the resultant probability of damage determined using a cumulative log-normal distribution function. Comparisons were made between the rotating and nonrotating missiles to determine if rotation did increase the probability of survival for the missile system.

In all scenarios studied, rotation significantly decreased the maximum skin temperature, increasing the probability of survival for the missile. The decrease was most dramatic for the walk attack, where an optimum rotation rate of .8 radians/second was established. For the 4-on-1 attack, rotation was effective, but required the maximum 1.6 radians/second rotation rate for best results. Finally, for the laser threat, rotation was effective for the scenarios studied, with the maximum rotation rate providing the greatest amount of protection. As a consequence, even at these relatively low rotation rates, rotation is an effective defense against the thermal threat.

THERMAL EFFECTS ON A

ROTATING MISSILE

I. Introduction

Background

Thermal energy is electromagnetic radiation travelling from a source at the speed of light. Normally, thermal energy, such as from the sun, produces no harmful effects. However, when enough thermal energy is absorbed in a short amount of time, it produces heating and melting of the absorbing material. This phenomenon is referred to as the thermal effect.

Past survivability studies have shown that missiles, because of their thin, metallic skin, are vulnerable to the thermal effect. This is because the missile surface absorbs enough energy to raise the skin temperature beyond the melting point, causing structural failure and destruction of the missile. Two sources capable of causing thermal damage to a missile are: the thermal pulse from a nuclear explosion, and a laser beam pulse.

When a nuclear weapon explodes near the surface of the earth, it creates a fireball emitting thermal radiation. The radiation from a single burst is emitted as a double pulse, the first pulse lasting less than a tenth of a second, and containing approximately one

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percent of the energy. The second pulse may last several seconds (up to ten seconds for a one megaton explosion) and contains ninety-nine percent of the total thermal energy.

Recent studies have shown that when a missile is subjected to multiple bursts, the thermal pulses overlap, having an additive or cumulative effect on the missile. For these cumulative burst scenarios, the thermal effect had a significantly larger lethal range than for multiple bursts considered separately. This lethal range was even greater than the lethal range for the blast effect. Thus, a missile is especially vulnerable to the cumulative thermal effect from a multiple burst attack.

If a missile survives the nuclear thermal threat, it may still be vulnerable to the thermal effect from a space-based laser. While the concept of a laser in space is not new, the Strategic Defense Initiative (SDI) has sparked a renewed interest in this type of weapon. Laser light has several properties that make it useful for weapons application. First, the intensity, or power per unit area, a laser can deliver to a target is very large. Secondly, laser energy is highly directional, allowing the intensities to be confined to a small area and to remain collimated for long ranges. Thus, a laser is capable of depositing a large amount of energy in a

short amount of time on a relatively small area.

Regardless of the source of thermal energy, the extent of damage to a target depends on the amount of radiation absorbed by a unit area of missile surface in a short interval of time. For a given surface material, only a small amount of the absorbed energy will be dissipated away by conduction, convection, or re-radiation. As a consequence, the absorbed energy is contained in a shallow depth of the surface, resulting in high temperatures that could damage the material. The purpose of a survivability study is to determine the amount of damage to the target and express it as a probability of survival. For thermal effects on a missile's skin, the probability of survival was calculated using the cumulative log-normal distribution function. Using this technique, a probability of survival was determined for each missile as a function of the missile's maximum skin temperature. A detailed discussion of the distribution function is in Hall (Hall, 1984: 94).

One possible way to decrease the amount of absorbed energy, and thus the skin temperature of the target, is to rotate the missile. Rotation moves radiated surfaces of the missile out of line of sight view from the source. The missile, in effect, acts as a shield against the thermal radiation. Also, rotation exposes

more surface, distributing the energy over a larger area, keeping the skin temperature below the sure-kill level.

Problem and Scope

The purpose of this thesis project was to show the effect of missile rotation on the skin temperature of a missile subjected to thermal radiation. The study focused on the cumulative thermal effects from a multiburst attack, and the thermal energy deposited by a hypothetical space-based laser on a missile during flight. The rotation rate was varied from 0-1.6 radians per second, with a maximum skin temperature and probability of survival calculated for each rotation rate. These maximum temperatures and probabilities of survival were compared to the nonrotating missiles to determine if rotation increases survivability. Also, an optimum rotation rate (one which keeps the missile skin temperature the lowest) was determined. The intent was to show that since rotation distributes thermal radiation over larger areas of the missile's surface, the thermal effect is reduced, and the missile's probability of survival increases.

For the multiburst scenarios, the burst-target missile system was the Peacekeeper close-spaced basing (CSB) system (see figure 1). This system was useful in
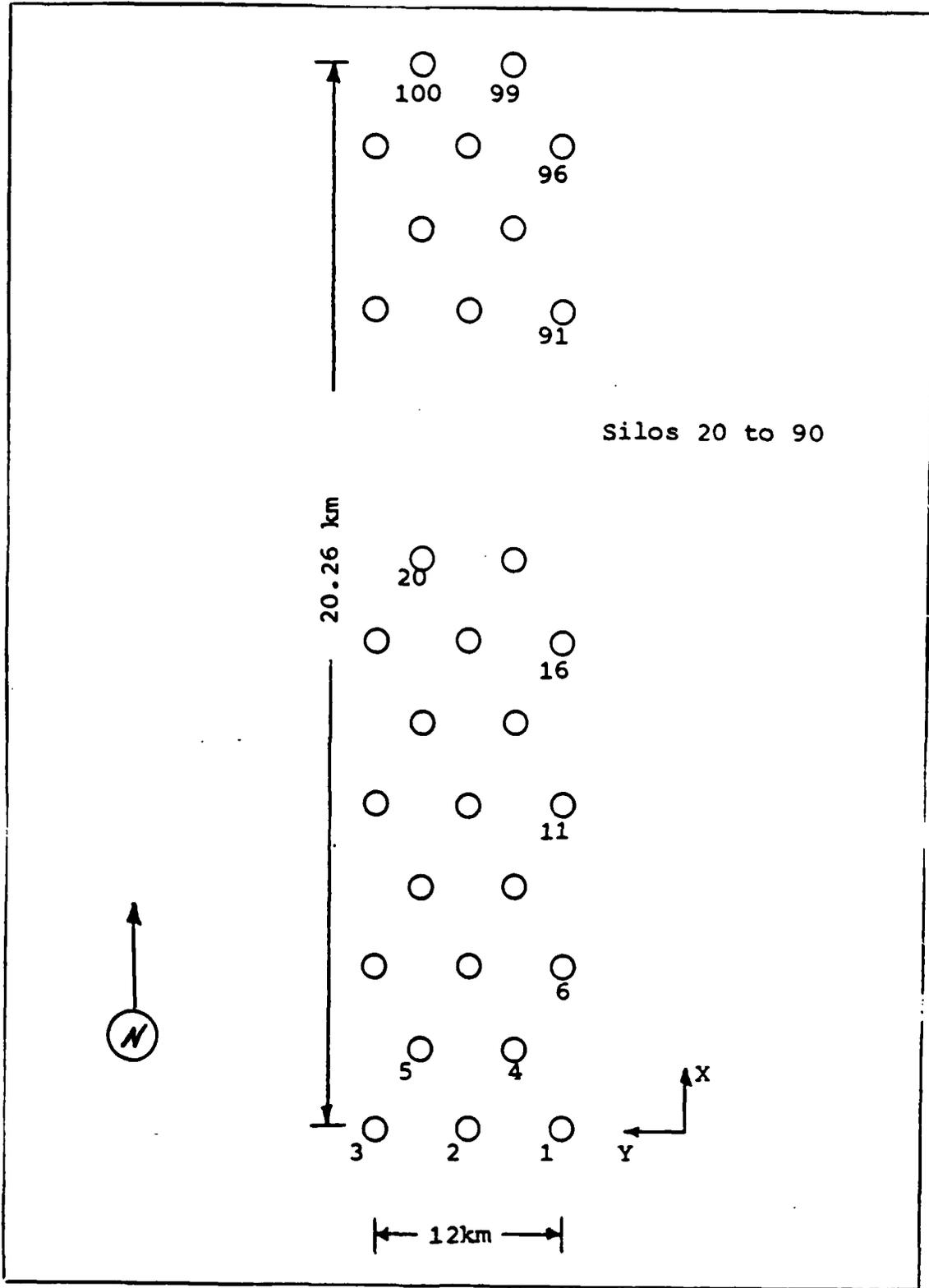
Fig. 1. Close-spaced Basing Missile Field

modelling how a rotating missile would survive a walk
attack. Also, several 4-on-1 attacks were studied.
These scenarios involved an isolated missile subjected
to four bursts, one burst occuring every two seconds.
The burst locations, relative to the launching missile,
were varied. The intent was to determine if an optimum
rotation rate was scenario dependent. The laser weapon
was a hypothetical space-based design with a maximum
absolute power of 10 megawatts. While no such system
exists, weapons of this type are considered possible.
Finally, the rotation rate was limited to 1.6 radians
per second. This maximum value was established by
studies conducted at the Air Force Institute of
Technology, Department of Aeronautics (Bandstra, 1985:
4).

Assumptions and Limitations

The following assumptions and limitations were made
to simplify the study:

1. Existing computer programs were used to
calculate skin temperatures for this analysis. Missile
flight characteristics were modelled using the
information in figure 2. The programs were modified to
account for the missile rotation, and the missile's
cylindrical shape.
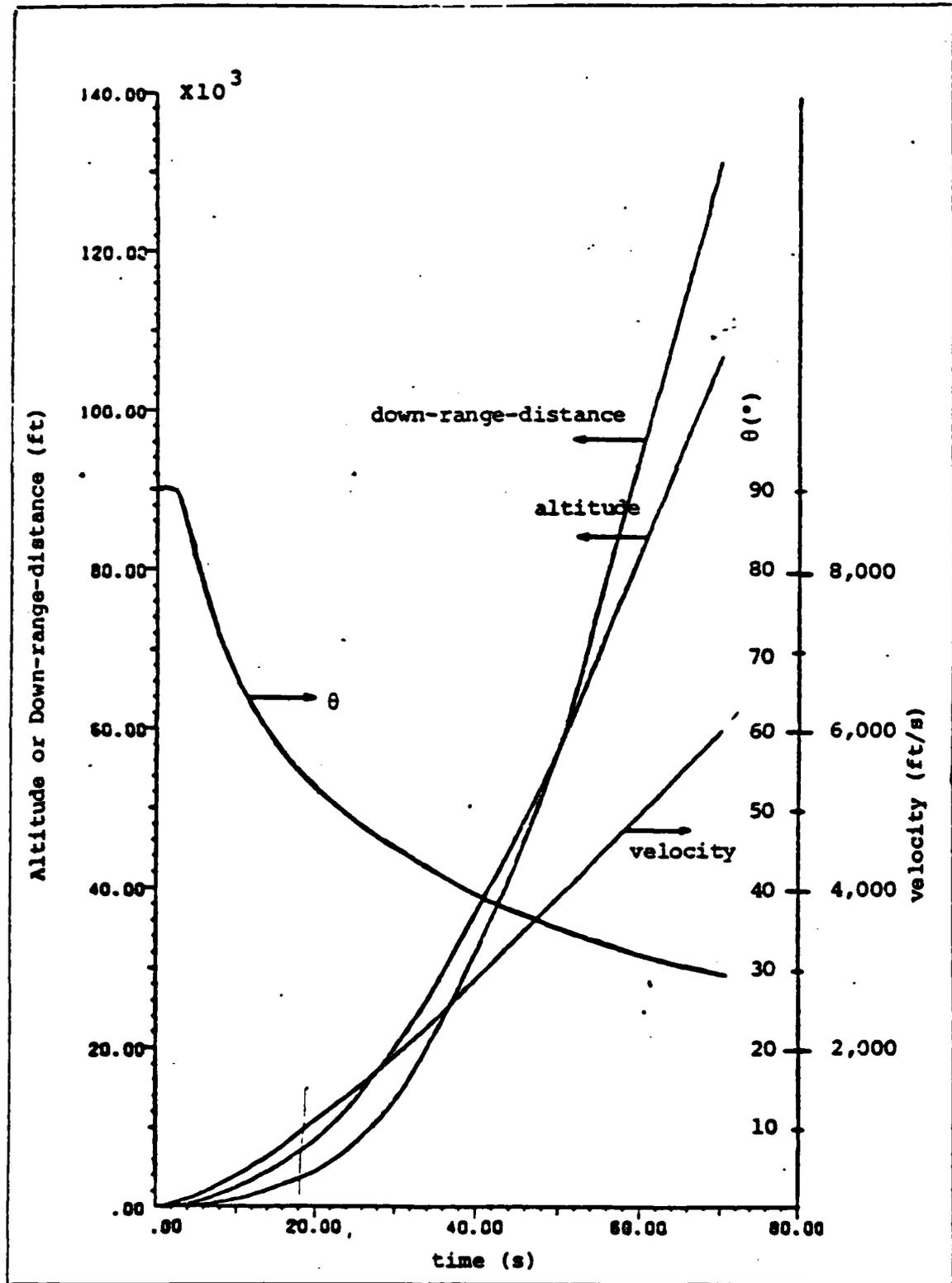
Fig. 2. Missile Characteristics

2. The reentry vehicles landed on their designated targets, i.e. no aiming error. This step allowed the programs to run on a personal home computer.

3. The rotation rate was constant. The system was assumed capable of reaching and holding the exact rotation rate.

4. The missile's cylindrical shape was modelled as a set of evenly spaced nodes of unit area. Three models (8, 16, and 32 node) were evaluated.

5. The laser weapon was a hypothetical space-based design. Beam generation, power requirements, or other beam propagation phenomena were not modelled.

6. The laser beam spatial profile was assumed to be flat. In otherwords, the intensity in every square centimeter of the beam spot was assumed to be constant. Exact spatial profiles are hard to determine for a high power laser, and thus a constant intensity profile was considered appropriate for this study (Bailey, 1985).

7. Laser beam pulses were restricted to one second. This was considered an appropriate tracking and power limitation (Bailey, 1984:41).

Approach

The following approach was used in calculating the probability of survival for a missile subjected to the

cumulative thermal effects from a multiburst attack.

Existing computer programs were used to calculate the

temperature on the missile's skin. These programs were

derived from an energy balance over a unit area of the

missile skin surface and a simplification known as the

thin skin approximation (Hall, 1984:12). The programs

were modified in two ways. First, the temperature was

calculated at several locations or nodes around the

circumference of the missile, simulating the cylindrical

shape of the missile. Second, the nodes were

repositioned for each time step, simulating the rotation

of the missile. In this manner, a distribution of

temperatures around the missile could be estimated. The

probability of survival for the missile was found by

using the highest temperature of any node on the missile

surface.

The following approach was used to find the

probability of survival for a missile subjected to a

laser pulse. Considering the inherent limitations in

focusing laser light, the spot size varied from 10 to 40

cm in diameter. Also, since the laser pulse was limited

to one second and the rotation rate was limited to 1.6

radians per second, the area of missile actually

irradiated was very small. Therefore, the missile

surface was modelled as a flat slab, divided into cells

of one cm^2 area. Using an iterative process, the amount

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of radiation absorbed and the temperature in each cell was calculated. At the end of the iteration, the cell with the largest amount of absorbed energy and thus the highest temperature was used to calculate the probability of survival for the missile.

Presentation

Chapter II contains a derivation of the model for the cylindrical shape of the missile, and missile rotation, as well as a discussion of the equations used to model laser energy deposition. Then, how these models were incorporated into existing computer programs is presented. Chapter III summarizes some of the *parameters and conditions used in this study, and why* certain parameters were chosen. Finally, Chapter IV presents the results of the study and Chapter V details the conclusions and recommendations.

II. <u>Theory</u>

This chapter contains the theory used to determine
the probability of survival for a rotating missile
subjected to thermal radiation. The first part of this
chapter deals with the cumulative thermal effect from
multiple nuclear weapon explosions. First, a derivation
of the missile's cylindrical shape is presented,
followed by an explanation of how the rotation of the
missile was calculated. The second half of the chapter
examines laser radiation. Specifically, the equation
used to calculate the amount of laser energy absorbed by
the missile surface is derived. Next, the laser spot
and missile surface are modelled to simulate rotation.
Finally, the technique used to calculate maximum
temperatures and probabilities of survival for the
missile, using these models, is explained.

<u>Derivation of the Model</u>
<u>for the Missile's Cylindrical Shape</u>

The missile's probability of survival for the
thermal threat from a nuclear weapon is calculated using
the maximum temperature reached during a burst scenario.
The temperature is calculated over a unit area of
missile skin surface using a simplification known as the
thin skin approximation. This approximation leads to

the following differential equation:

$$a \frac{dT(t)}{dt} = \alpha \frac{dF_{incident}}{dt} - h[T(t) - T_{air}(t)] \qquad (2.1)$$

which can be solved using the method of finite differences. After making the appropriate substitutions, equation (2.1) becomes:

$$T_2 = \frac{[T_1(a - \frac{h \cdot t_{max}}{2}) + h \cdot t_{max} T_{air} + \alpha \Delta Q]}{(a + \frac{h \cdot t_{max}}{2})} \qquad (2.2)$$

where

  T_2 = temperature at the end of the jth time step (K)

  T_1 = temperature at the beginning of the jth time step (K)

  a = $C_p \rho d$

  α = absorptivity of missile skin

  Q = total thermal fluence incident on the missile during the jth time step (J/m^2)

  h = local convective heat transfer coeffecient (J/m^2-s-K)

  T_{air} = temperature of ambient air at missile altitute (K)

  t_{max} = time step (sec); $t_{max} = .0417 * Y^{.44}$, (Y-yield in kilotons)

For a more detailed derivation of this equation, refer

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to Hall (Hall, 1984:12-18). Using equation (2.2), the temperature of the missile surface can be found.

In past studies the missile's cylindrical shape was not considered, but rather the missile surface was modelled as a single flat slab. This model, however, does not adequately correct for the geometry between the slab and each burst point. For example, when a missile was subjected to more than one burst, the thermal radiation from each burst was assumed to strike the slab. A correction factor was calculated for the missile's flyout angle, but no correction was made to account for the angle between the burst point and the slab. Using the cumulative thermal energy, equation (2.2) was used to calculate the temperature of the missile. In reality, the amount of radiation absorbed by the slab also depends on the geometry between the slab and the burst. In the extreme case of four bursts completely surrounding a missile, it would be incorrect to assume one spot, or slab, received all of the thermal energy from all four bursts. Actually, the thermal radiation would be distributed around the surface of the missile, and the resultant temperature anywhere around the missile's circumference would be much less than the temperature calculated assuming one slab received all of the thermal radiation. In addition, a rotating missile would also distribute the thermal radiation, reducing

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the amount any one point on the surface absorbed.

For this study a simple model was developed to approximate the cylindrical shape of the missile. Instead of one flat slab of unit area, several evenly placed slabs, or nodes were used. Figure 3 shows how an eight node model would appear.
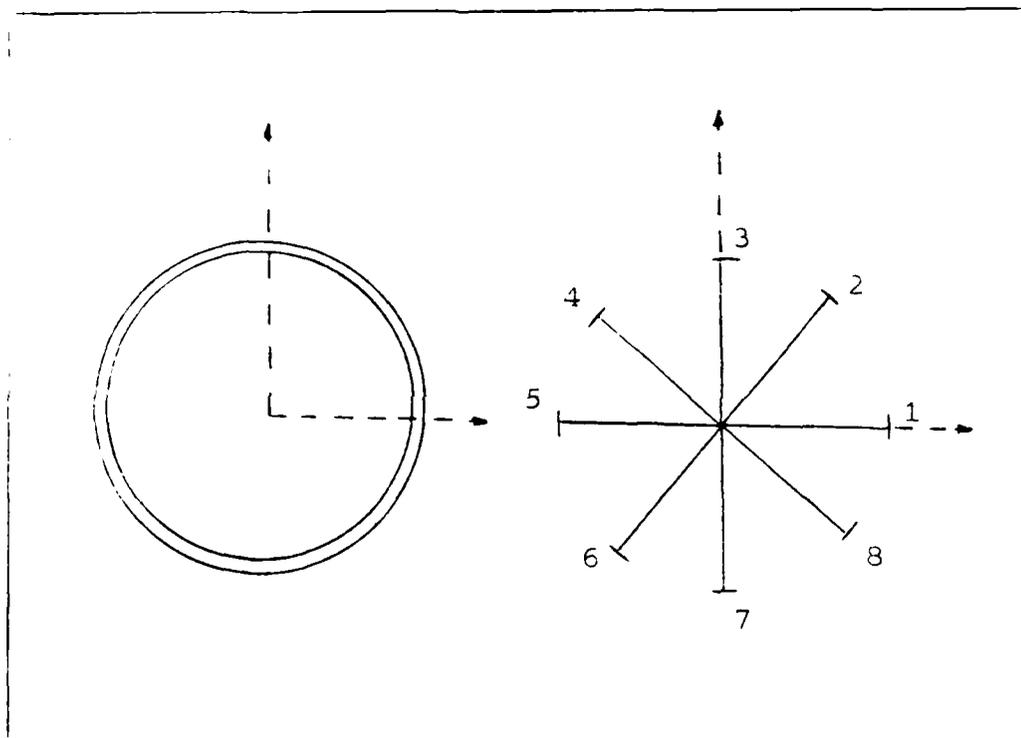
Fig. 3. Missile Circumference and Eight Node Model

The temperature for each node is calculated for each missile-burst encounter using equation (2.2). Thus, for each time step j, equation (2.2) was calculated eight times, once for each node. The difference in temperature for each node is related to

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how much energy was incident perpendicular to the
surface. Obviously, when the shape of the missile is
considered, the surface facing the burst receives the
most energy, while the surface on the back receives no
energy. Also, when allowed to rotate, the nodes could
be removed from the side receiving radiation decreasing
the amount of energy any one node would receive.
Therefore, to account for the fact that each node
receives a different fraction of thermal energy,
dependent on its position relative to the burst, a
correction factor was needed. This rotational
correction factor (RF) determines the fraction of
thermal energy incident perpendicular to each node.
Appendix A has a complete derivation of the rotation
correction factor. Now, with the RF term included,
equation (2.2) becomes:

$$T_2(n) = \frac{[T_1(n)(a - \frac{h \cdot t_{max}}{2}) + h \cdot t_{max} T_{air} + \alpha \Delta Q * RF(n)]}{(a + \frac{h \cdot t_{max}}{2})} \quad (2.3)$$

where

      n = the node of interest, $n = 1, 2, \ldots 8$.

    $RF(n)$ = rotation correction factor for node n,
                  determines the amount of thermal energy
                  incident on each node at time step j.

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Thus, by examining equation (2.3) the temperatures at various nodes are related to the amount of energy absorbed by each node. The value for each rotation factor was determined by its position relative to the burst, and rotation constantly changed these positions.

Rotation of Missile Nodes

The following definitions are needed to describe the rotation of the missile:

t=time of missile skin exposure to thermal radiation. t is also equal to the time of thermal energy emission since radiation travels at the speed of light.

ω =rotation rate of missile in radians per second, rotation rate is constant, no angular acceleration

Δt =time, in seconds, between succeeding time steps (i.e. $\Delta t_j = t_{j+1} - t_j$)

As stated before, the cylindrical shape of the missile was modelled using a set of evenly spaced nodes of unit area. The position of the nodes is determined by their angular displacement, theta (θ), and position vector (r). Figure 4 shows an eight node model with the appropriate theta and r values.

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Note: r = missile radius for all nodes
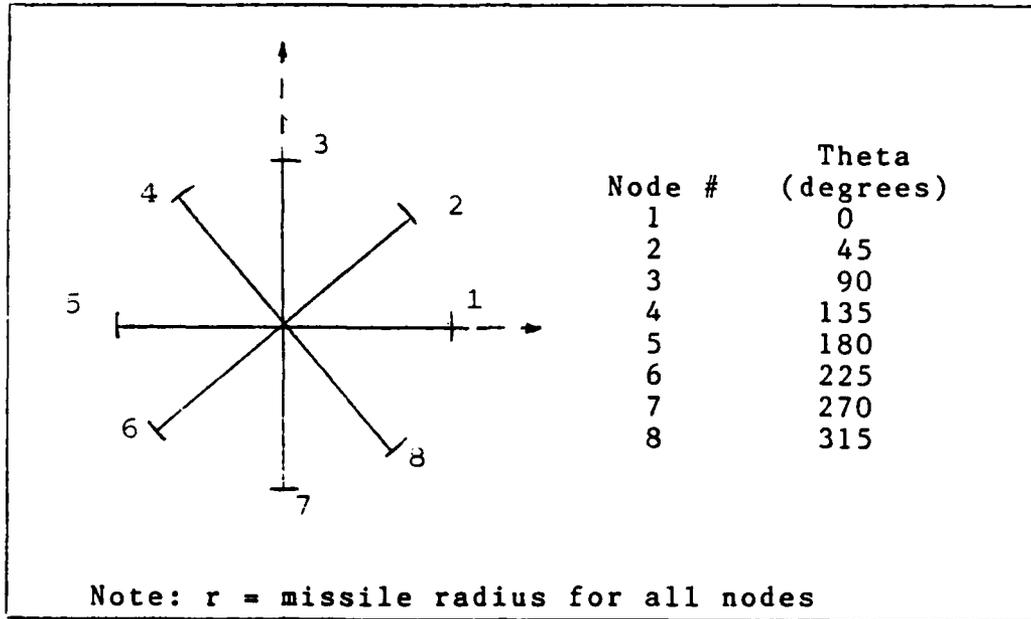
Fig. 4   Node Positions at t=0

Since the missile radius, r, remains constant the
nodes' new positions will be defined by changes in their
angular displacement only. Therefore, for a constant
rotation rate, the new positions can be found using the
equation:

$$\theta_{new} = \theta_{old} + \omega * \Delta t \qquad (2.4)$$

For example figure 5 shows the eight nodes at new
positions for a rotation rate of .5 radians/sec, and a
t of .59 seconds.

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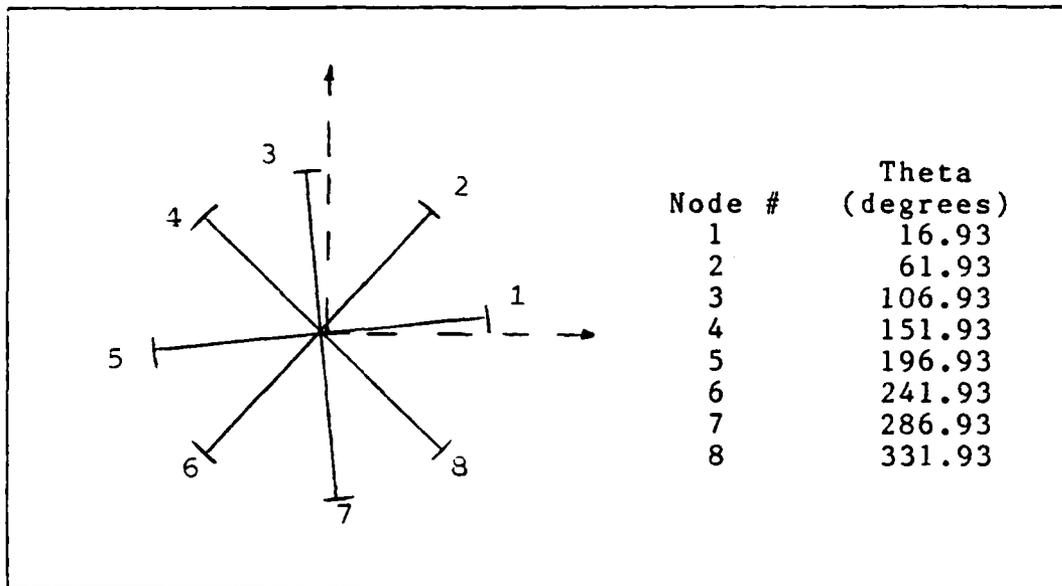
Fig. 5   New Node Positions

Thus, the new node positions can be found for each time
step, simulating the rotation of the missile.

Derivation of the Equation
for Laser Energy Absorption

Like the thermal radiation from a nuclear
explosion, only a fraction of the laser energy is
absorbed by the missile surface. This fraction is known
as the absorption coefficient, α . Also, the depth of
penetration, or skin depth, δ , is very small. Thus, the
surface is subjected to local heating and melting
(Bailey,1984:42). Appendix B contains sample
calculations for skin depth, and absorption coefficient
for laser energy.

Assuming the absorption coefficient is known, the

rate of energy transfer into a material surface is:

$$\frac{dH}{dt} = \alpha I \qquad (J/cm^2\text{-}s) \qquad\qquad (2.5)$$

where

$\qquad$ I = radiation intensity $(J/cm^2\text{-}s)$

$\qquad$ α = absorption coefficent, or absorptivity

The total energy absorbed in a given time interval will
be:

$$\Delta H = \frac{dH}{dt} t = \alpha I \Delta t \qquad (J/cm^2) \qquad\qquad (2.6)$$

If Δt is replaced by a finite time step, j, arbitrarily
chosen as .01 seconds, then equation (2.6) gives the
amount of energy deposited in each square centimeter of
the laser spot during any time step. Knowing the amount
of laser energy deposited into the missile, equation
(2.2) can be used to find the temperature on the missile
surface.

Calculating Laser Spot and
Missile Surface Rotation

For this study, the laser spot size was calculated
using information from Bailey (Bailey,1885:42-66).

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Using optimistic laser power and focusing capabilities,
the spot size was still quite small when compared to the
missile surface. For this reason, the missile surface
was modelled as a flat slab. In order to model missile
rotation, the missile surface was divided into cells,
one cm^2 in area. Also, the intensity of the laser was
assumed constant across the spot area. This is a
reasonable assumption for a very high powered laser
(Bailey, 1985). Thus, using equation (2.6), the energy
deposited in each cell during each time step j, can be
calculated. Since the intensity is constant, only a
strip of cells were considered in the calculation.
Figure 6 shows a laser spot and a strip of cells.
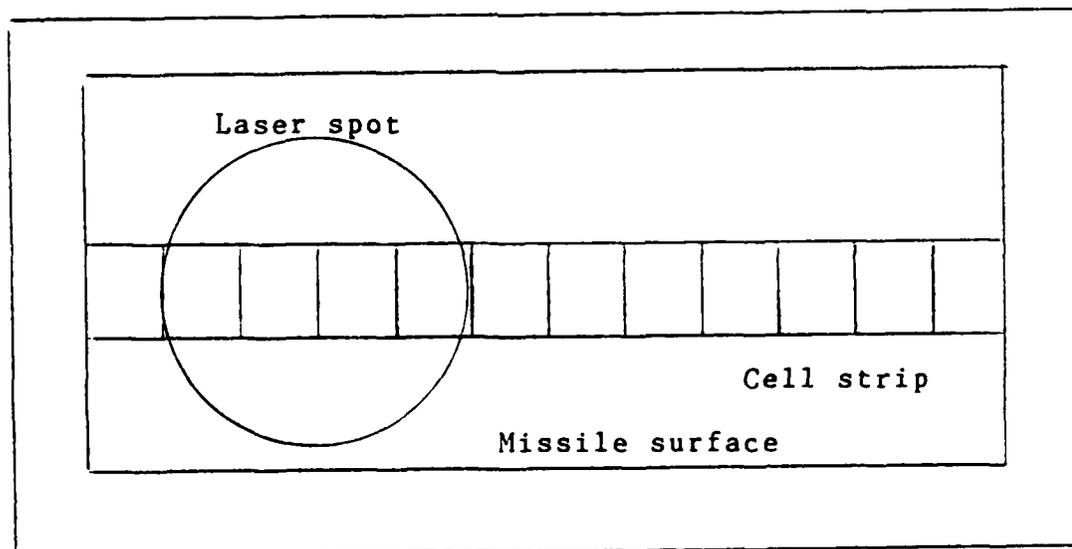
Fig. 6.   Laser Spot and Cell Strip

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With no rotation, the spot would deposit the laser
energy on the same cells for each time interval, with
heating and possible melting of the surface. For
rotation, however, the spot would deposit energy on
different cells as the missile surface moved,
distributing the energy and reducing the amount of
energy any one cell absorbs.

The rotation of the slab through the laser spot was
determined by first calculating the linear velocity of
the surface of the missile using the equation:

$$v = \omega * r \qquad (cm/sec) \qquad\qquad (2.7)$$

where

       v = linear velocity of missile surface
         (cm/sec)
       ω = rotation rate (radians/sec)
       r = missile radius (cm)

For example, for a rotation rate of .8 radians/sec and
missile radius of 116.84 cm, the surface velocity is
approximately 93 cm/sec. The distance, s, the slab
travels in any time interval is found by:

$$s = v * \Delta t \qquad (cm) \qquad\qquad (2.8)$$

If t is replaced by j, then for each time step, the
distance the surface moved in relation to the spot is
known. The distance, s, determines which cells are

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radiated by the laser spot. The amount of energy each cell receives for each time step is stored in a one dimensional array. Obviously, when the laser spot overlaps a cell on the surface, the energy in the cell increases, causing higher temperatures.

Adapting Models to Computer Programs

Because direct experimentation is impossible, computer programs are used extensively to model nuclear weapons effects. The groundwork for this study was introduced in NE 6.95, Nuclear Survivability of Systems. Also, Hall modified and improved the thermal model to include the cumulative thermal effects from a multiburst attack (Hall, 1985:121-134). This program, called "Therm", was modified to account for the missile's cylindrical shape, missile rotation, and laser energy deposition.

In order to solve equation (2.3), an iterative method using a finite time step was used. Specifically, once the missile launch time, lt, the first burst time, tb1, and the total number of time steps were known, the midpoint of each time step was calculated. At these times, missile characteristics, ambient air temperature, and the heat transfer coefficient were calculated and stored in one dimensional arrays. In addition, using

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equation (2.4), new node positions were found. Then, using equation (A.4), the new rotational correction factors were calculated to determine the amount of radiation incident on each node. As the temperature for each node was calculated, a distribution of temperatures around the circumference of the missile was found. The iteration process continued, with the maximum temperature achieved used to calculate the probability of survival for the missile.

The same computer program was changed slightly to calculate the probability of survival for a missile subjected to a laser attack. Again, at the midpoint of each time step, the missile characteristics, ambient air temperature, and heat transfer coefficient were calculated and stored in arrays. Using equation (2.8), the distance the missile surface had moved was calculated. Representing the missile surface as a one dimensional array, this distance determined which cells, or array locations, were radiated for that time step. With the appropriate cells identified, the amount of energy for each cell was calculated using equation (2.6), and stored in the array. At the end of the iteration, the cell with the largest amount of energy was used to determine the maximum temperature, and probability of survival for the missile.

The basic algorithm for these two models is shown

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in table I.   In addition, Appendix E. has a complete
listing of the computer program "Therm".

TABLE I

ALGORITHM FOR FINDING THE MAXIMUM SKIN TEMPERATUE

FOR A ROTATING MISSILE

1. Knowing lt and tbl, calculate and store missile
    velocity, altitude, down-range-distance,
    at $t = t_o + (j-.5)*T_{max}$, where
    $j=1,2...11$.

    Calculate and store T_{air} and h at same times

    Knowing the burst number, and the times
    of the burst, calculate and store the
    amount of energy emitted by the thermal
    source, and, if applicable, the height
    of burst.

2. Set $j=1$, $T_1 = T_{air}$ at $t = t_o$, T_2 to be
    any number greater than T_1, and the number
    of bursts $nb = 1$.

3. If $T_2 < T_1$ and $j < = 10$ then:
    a. The current time step is $j = j + 1$

    b. At time j*tmax, determine if another burst

        has occurred. If so, $nb = nb + 1$.

    c. For each burst k that occurs:
        1. Calculate SR, theta, and thetaprime.
            If burst k has just occurred within
            the time step, missile
            characteristics must be
            re-calculated.

        2a. Calculate the total thermal
            energy emitted by the burst.
            Calculate RF(n) for each node,
            and store the amount of absorbed
            energy of each node

        2b. Calculate the distance the slab moved
            if laser energy problem, and identify
            and store the energy received by each
            cell.

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d. Calculate T_2 knowing h; and the total energy absorbed by each node, or each cell whichever is applicable.

e. For each node, or cell:
   If $T_2 < T_1$ then $T_2 = T_1$

f. Return to condition in step 3. If either test fails, go to step 4

4. MaxT = T_1

Chapter III. <u>Conditions</u> <u>and</u> <u>Limiting</u> <u>Parameters</u>

In order to calculate the probability of survival
for a missile against any thermal threat, several
conditions and limiting parameters were required. For
the thermal threat from multiple nuclear explosions, the
conditions and parameters were the same as those used in
a similar study by Hall (Hall,1985:31-34). A brief
description of some of the conditions is presented
first, and the remaining values listed in table II. The
remainder of this chapter deals with the conditions and
parameters required to determine the probability of
survival for a missile against a laser threat. These
values were developed from notes given by Dr. W. Bailey
(Bailey,1985), and are summarized in table III.

From a similar study by Hall, several simplifying
conditions and parameters were developed and used in
this study. First, the RV aiming error was zero, thus
deleting the requirement for calculating a circular
error probable. This assumption reduced computing time
significantly, but did not affect the results
(Hall,1985:48). Second, the location for calculating
the local heat transfer coefficient, h, was assumed to
be the third stage joint on a generic missile. This
position (X_m = 5.5 m) represents a point where an
average amount of convective cooling occurs along the

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missile skin (Hall, 1985:34). Finally, the maximum number of bursts was limited to four. While this was a rather arbitrary limit, the cumulative effects of four bursts adequately demonstrates the difference between a rotating and nonrotating missile. In addition, increasing the number of bursts increases the computing time, but does not change any other aspect of the attack.

Determining Minimum Intensity Required on Target

For this study, a laser kills a target if it deposits enough thermal energy per unit area in a short amount of time, to raise the missile skin temperature above the sure-kill level (809 K). Using the thin skin approximation, the minimum intensity (W/cm^2) required to insure a thermal kill can be found. Sample calculations are in Appendix C, and they show that approximately 2000 W/cm^2, delivered for one second, will kill a nonrotating missile. Therefore, for this study, regardless of the spot size considered, the minimum intensity incident on the surface of the missile was 2000 W/cm^2.

TABLE II

CONDITIONS AND PARAMETERS FOR CUMULATIVE THERMAL THREAT

System:
 Close-Spaced Basing, of Peacekeeper Missiles
 (see figure 1)

Threat Conditions:
 Walk attack starting at silo #1 and continuing
   every 2 seconds on successive silos
 Weapon Yield: 2 MT
 Height of Burst: 0 m
   For surface bursts, tf = .18
   (Glasstone and Dolan, 1977:319)

Missile Conditions:
 Missile velocity, altitude, down-range-distance,
   and flight path angle shown in figure 2 as
   a function of time
 Skin material: Aluminum
   $K = .0001$ m^2/s
   $\rho = 2700$ kg/m^3
   $\alpha = .50$
   $C_p = 900$ J/kg-K
   $I_{ss} = 619$ K
   $I_{sk} = 809$ K
 Skin thickness: d = .001 m
 Rotation Rate: 0 - 1.6 radians/s

Probability Conditions:
 RV aiming error: none
 Probability of damage based on intensity and
   calculations using the cumulative log-normal
   distribution function
   $P_d(I_{ss}) = .98$
   $P_d(I_{sk}) = .02$

Parameters:
 Maximum number of bursts considered: maxb = 4
 Maximum number of time steps needed: 11
 Heat transfer coefficient calculated at $x_m = 5.5$ m

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TABLE III

CONDITIONS AND PARAMETERS USED IN LASER THREAT STUDY

System:
    Peacekeeper Intercontinental Ballistic Missile

Threat Conditions:
    Laser: Space based, continuous power,
        chemical laser
        Maximum Power = 10 MW
        Aperture = 10 m
        Altitude = 400-800 km
        Spot size = 10 - 40 cm
        Minimum Intensity required on target:
            2000 W/cm^2 incident normal to surface
        Maximum pulse time = 1 second

Missile Conditions:
    Velocity = 5 km/s
    Altitude = 100 km
    Skin material: Aluminum, properties in table II
    Skin thickness: d = .001 m
    Rotation Rate: 0 - 1.6 radians/s

Probability Conditions:
    Same as table II

Parameters:
    Maximum number of pulses on target: 1

Determining Laser
Threat Conditions

As stated before, the laser weapon was assumed to have a maximum absolute power of 10 MWs, with an aperture of 10 m. While these are optimistic parameters, the possible deployment of such a weapons in the future is considered feasible (Bailey, 1985). In order to calculate the probability of survival for a missile subjected to a laser pulse, a specific laser-missile scenario was developed from notes given by Dr. W. Bailey (Bailey, 1985: 42-62).

The laser's initial intensity is given simply by the equation: Intensity = Power/Area. For this particular laser, $I_o = 1.27*10^5$ W/cm^2. To be a lethal beam, it must be focused to a small spot on the target. The spot radius for a given distance, Z, is determined by:

$$W(z) = \frac{.6*\lambda*Z}{W_1} \qquad (3.1)$$

where

λ = laser wavelength (m)

Z = distance from laser to target

W_1 = laser aperture radius (5m)

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Table IV shows several values of Z, and the appropriate spot radii.

TABLE IV

SPOT RADII FOR VARIOUS DISTANCES FROM LASER TO TARGET

Distance (km)	Spot Radius (cm)
250	10
420	20
625	30
800	40
2000	100

Assuming no beam jitter, the intensity on target is defined as:

$$I_t = I_o \; \frac{W_1^2}{W(z)^2} \; [\text{absorption} + \text{scatter}] \quad (3.2)$$

where

I_t = intensity on target (W/cm^2)

I_o = initial intensity of laser (W/cm^2)

W_1 = laser aperture radius (5m)

$W(z)$ = spot radius (cm)

According to Bailey, for the altitudes considered in this scenario, absorption and scatter of the beam is negligible (Bailey, 1985:9-11). Therefore, the intensity on target is simply:

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$$I_t = I_o \frac{W_1^2}{W(z)^2} \qquad (W/cm^2) \qquad\qquad (3.3)$$

The maximum spot size, and thus the highest altitude the laser could be stationed and still deliver a lethal intensity can be found using equation (3.3) and solving for $W(z)$. Rearranging the equation:

$$W(z) = [I_o \frac{W_1^2}{I_t}]^{.5} \qquad (m) \qquad\qquad (3.4)$$

where, for this specific case,

$I_o = 1.27 * 10^5$ W/m^2

$I_t = 2.00 * 10^7$ W/m^2

$W_1 = 5m$

$W(z) =$ maximum spot size

$W(z)$ is approximately 40 cm. This means that a 10 MW laser, attacking targets approximately 800 km away, will produce a spot with a 40 cm radius, and deposit approximately 2000 J/cm^2 on the target in one second. This is sufficient to kill the target. For closer distances, the power required to produce the desired intensity is decreased as the spot size decreases. However, for this study, the intensity on target was assumed to remain constant at 2000 W/cm^2, regardless of the spot size being considered.

Chapter IV Results and Discussion

The main objective of this thesis was to determine whether rotation increased the probability of survival for a missile subjected to the thermal threat. The results from the rotating case were compared to the nonrotating case for both sources of thermal energy: nuclear weapons explosions, and laser pulses. The comparison showed that rotating missiles experience a significant decrease in the maximum skin temperature regardless of the source of the thermal energy. Thus, rotation is an effective defense against thermal radiation.

The results for a missile subjected to the cumulative thermal effect from multiple bursts of a walk attack are presented first. In all cases the time step was $t_{max}/2$. As a result, the maximum temperature change between time steps was less than seven degrees. Thus, accurate temperature rises were calculated while keeping the computing time to a minimum. To begin, a comparison between the 8, 16, and 32 node models was made to determine which model best simulated the missile's cylindrical shape. Next, the effect of rotation on the maximum temperature, and probability of survival of a missile are given. These results show that an optimum rotation rate exists. Next, the scenario is extended to

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show the sure-kill and sure-safe regions for the entire

missile field when every missile is rotating at the

optimum rotation rate. In addition, the results for a

missile subjected to a 4-on-1 attack are presented.

Under this type of attack, a faster rotation rate is

desirable. Finally, a comparison is made betweeen the

blast effect, and the thermal effect when rotation is

considered. These results show that rotation decreases

the sure-kill region significantly, reducing the

devastating effect of cumulative thermal radiation.

In a similar manner, the effect of rotation on

maximum temperature and probability of survival are

presented for the laser energy threat. This comparison

shows that for the scenarios investigated, rotation can

significantly increase the probability of survival for a

missile. Finally, the effect of spot size on rotation

is examined, emphasizing that large spot sizes, when

coupled with sufficiently high energy densities, are

difficult to defend against.

Comparison between 8, 16, and 32 Node Models

Figure 7 shows the probability of survival versus

rotation rate for missile #41 using an 8, 16, and 32

node model. The 16, and 32 node models agree over the
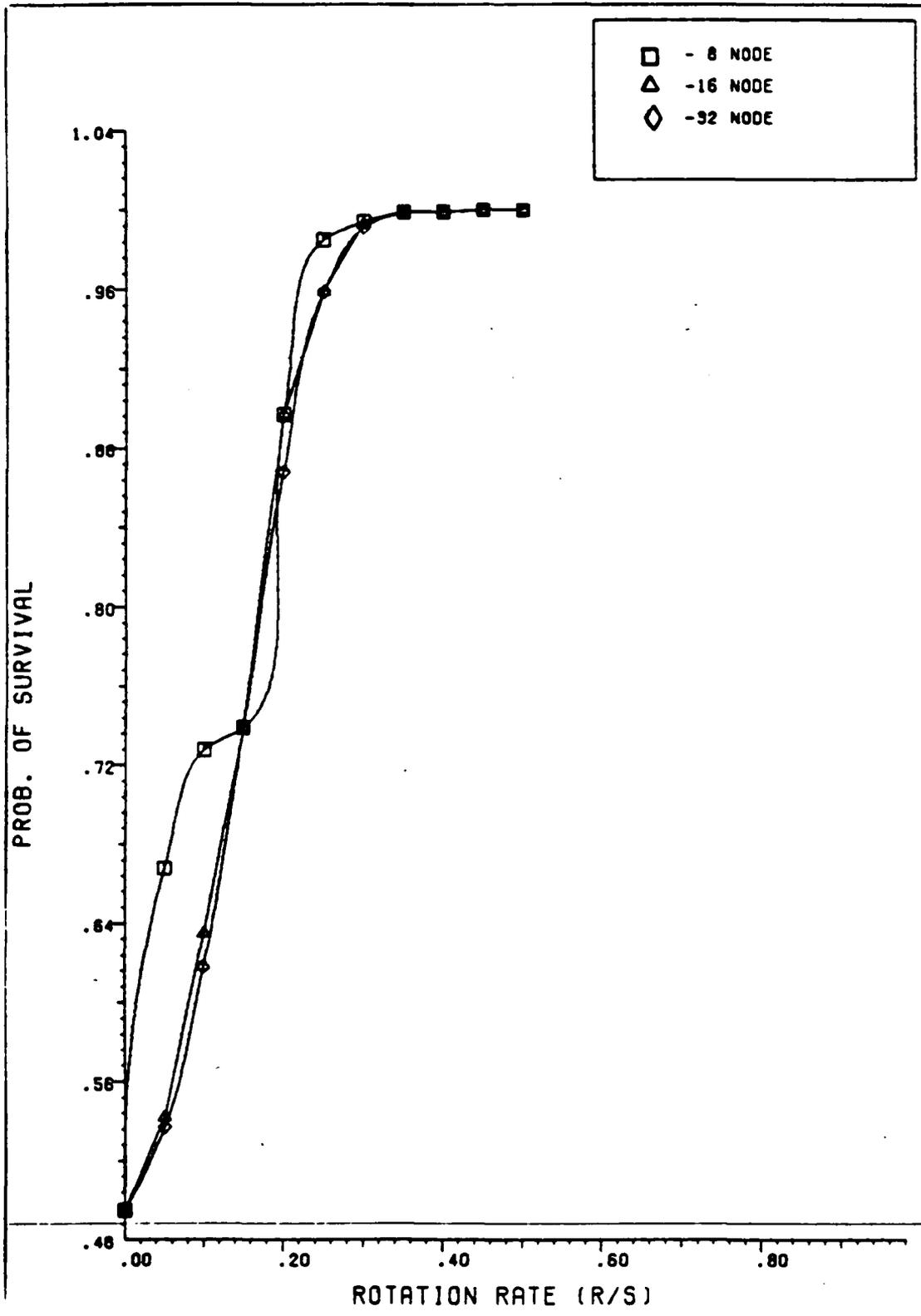
Fig. 7. Model Comparison - Ps. vs. Rotation Rate

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entire range of rotation rates, but the 8 node model
oscillates in the lower rotation rates. Computing times
did increase, but not significantly. Therefore, to
insure accuracy while keeping the computing time to a
minimum, the 16 node model was chosen for all subsequent
results.

Effect of Rotation on Temperature
and Probability of Survival for
Multiburst Case

Figure 8 shows the maximum temperature of any node
versus rotation rate for missile #41 subjected to four
bursts. The missile was launched at the same time that
silo #1 was hit, and fireball rise was considered.
Tabulated data for the curve is in Appendix D.

The effect of rotation on maximum temperature is
clearly illustrated in figure 8. As the rotation rate
increases, the temperature decreases to a minimum, and
then remains relatively constant, oscillating
approximately 20 degrees above the absolute minimum.
The minimum rotation rate correspondes to a period of
rotation of approximately eight seconds. For faster
rotation rates the nodes return to their beginning
positions too quickly, causing higher temperatures.
Another minimum is seen at approximately twice the
period (1.6 radians/sec). The drastic temperature

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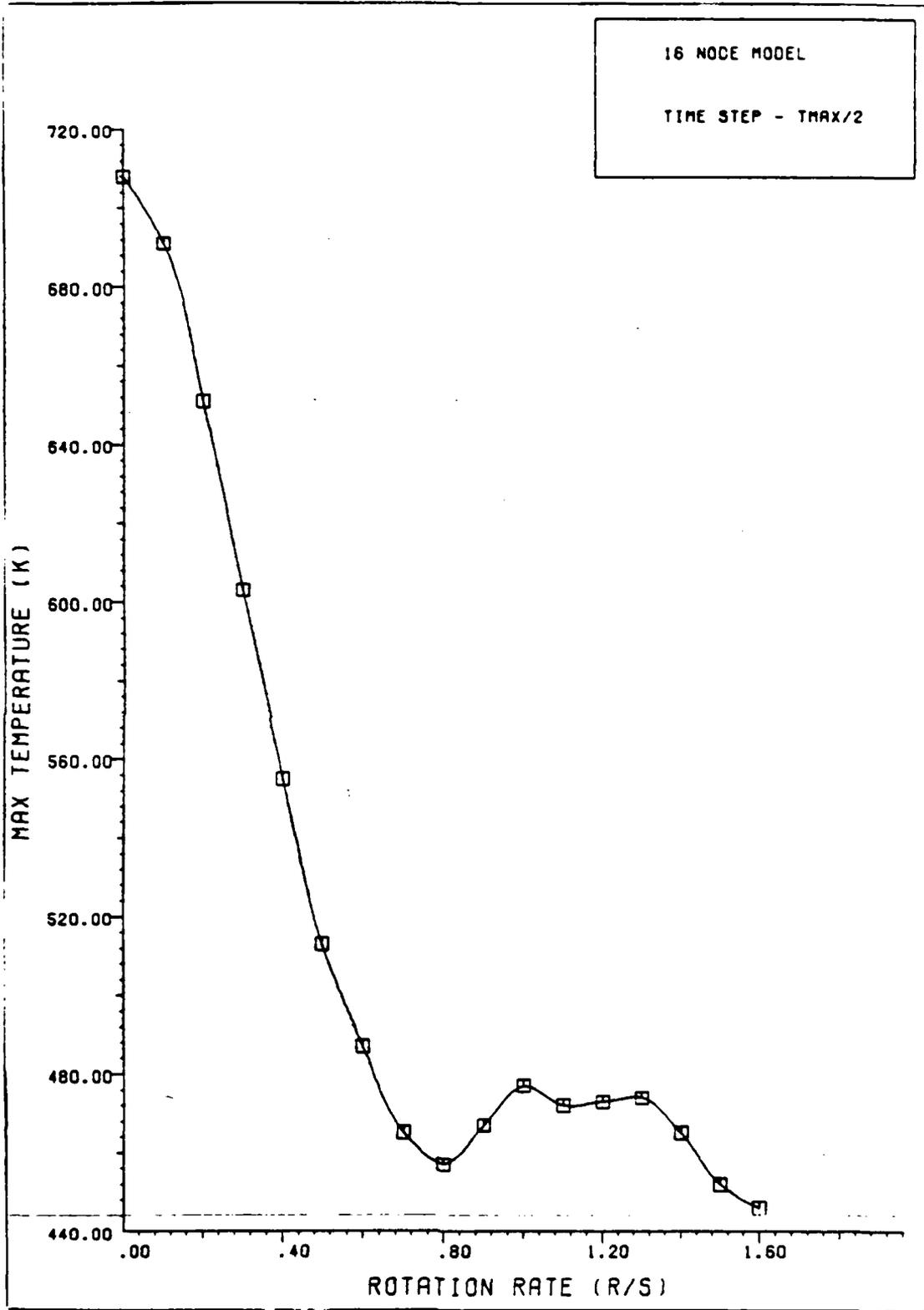
Fig. 8. Max Temperature vs. Rotation Rate

decrease occurs because the rotation constantly moves the nodes, shielding them from radiation, while exposing new nodes (missile surface) to the radiation. This prevents any one node, or point on the surface of the missile from receiving too much radiation. Also, when shielded, convective cooling can be more effective, allowing the nodes to reach lower temperatures before being reradiated on their return trip.

Figure 9 shows the probability of survival versus rotation rate for the same missile. This figure shows how increasing the rotation rate increases the probability of survival. However, the probability of survival is one at a much lower rotation rate (.4 radians/sec) than the rotation rate where the minimum temperature occurs (.8 radians/sec). This happens because the probability of survival is calculated using a cumulative log-normal function. Thus, once the sure-safe temperature is reached, the probability of survival is essentially one. Therefore, the optimum rotation rate was defined to be the rotation rate that produced the lowest missile skin temperature. For all missiles in the close-spaced base system, the optimum rotation rate was .8 radians per second.
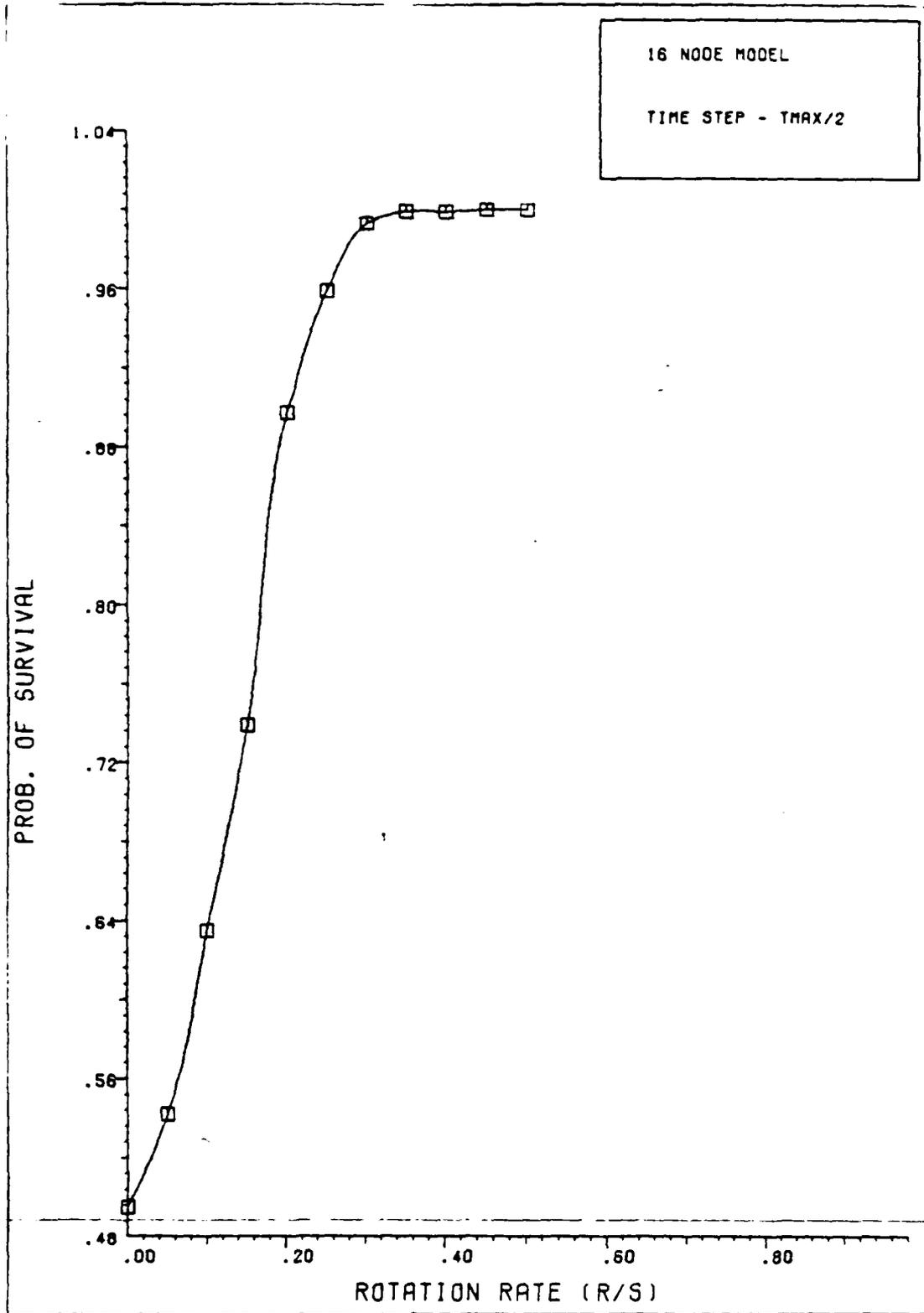
Fig. 9. Prob. of Survival vs. Rotation Rate

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Comparing the Rotating
and Nonrotating Cases

Table IV shows a comparison of maximum temperature

and probability of survival for several missiles at no

rotation, and at the optimum rotation rate.

TABLE IV

COMPARISON OF MAXIMUM TEMPERATURES AND PROBABILITY
OF SURVIVAL FOR NO ROTATION AND OPTIMUM ROTATION

Missile launch time:	0 sec
Time of first burst:	0 sec
Time between bursts:	2 sec

1 cell CEP

Optimum rotation rate: .8 radians/sec

Missile#	No Rotation		Optimum Rotation	
	MaxT (K)	Ps	MaxT (K)	Ps
28	1638	0.00	843	0.00
29	1390	0.00	735	0.28
30	1383	0.00	731	0.31
31	1169	0.00	645	0.92
32	1178	0.00	645	0.92
33	1160	0.00	640	0.93
34	1015	0.00	578	0.98
35	1011	0.00	577	0.98
36	885	0.00	527	0.99
37	889	0.00	527	0.99
38	880	0.00	524	0.99
39	789	0.05	486	1.00
40	787	0.05	486	1.00
41	708	0.49	454	1.00
42	680	0.50	440	1.00
43	670	0.54	436	1.00
44	645	0.92	430	1.00
45	640	0.93	430	1.00

For this thesis, the sure-safe limit is defined by a probability of damage of .02, and the sure-kill limit by the probability of damage of .98. Any values lower than .02 are rounded to 0, and any values higher than .98 are rounded to 1. Any missile not listed on table IV has a probability of survival of 0 or 1, depending on the missile's position.

Another way of presenting the values given in table IV is by using figure 1 to illustrate the sure safe and sure-kill regions. Figure 10 shows the two regions for the values in table IV. Comparing these results shows that rotation significantly decreases the sure-kill region for thermal effects.

Comparing Cumulative Thermal Effects to Blast Effects

According to a recent study, the cumulative thermal effect from a multiburst attack is more lethal than the (noncumulative) blast effect (Hall, 1985:52). Table V shows the probability of survival for noncumulative blast effects.
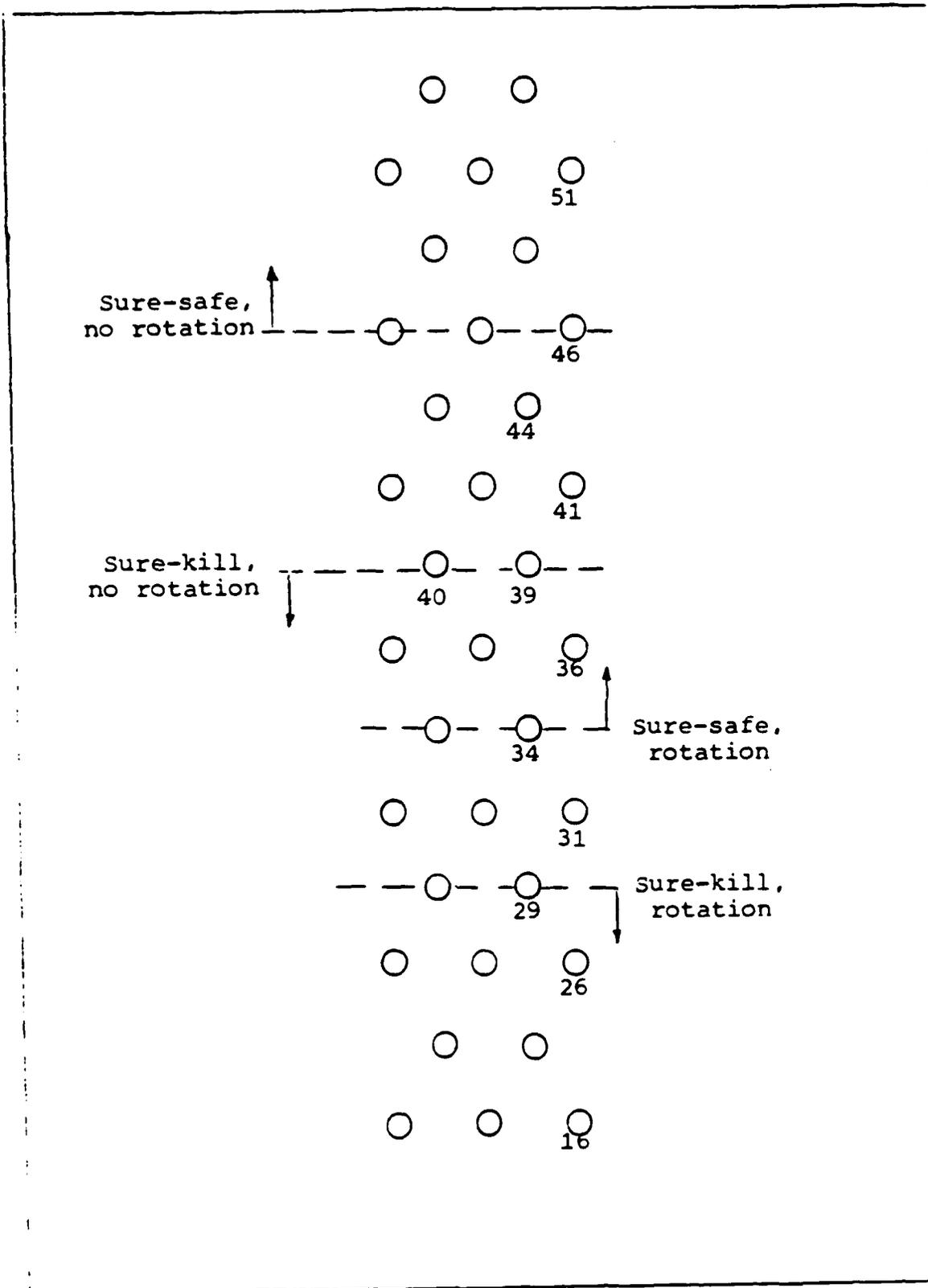
Fig. 10. Location of Sure-kill and Sure-safe Regions

TABLE V
RESULTS FOR NONCUMULATIVE BLAST EFFECTS

Missile launch time: 0 sec
Time of first burst: 0 sec
Time between bursts: 2 sec

Missile #	Prob. of Survival
23	0.000
24	0.072
25	0.096
26	0.590
27	0.626
28	0.750
29	1.000

Comparing these results to table IV shows that the blast
effect is overwhelmed by the cumulative thermal effect
for nonrotating missiles. However, for missiles
rotating at the optimum rotation rate, the sure-safe and
sure-kill regions are decreased significantly. Figure
11 shows these regions for rotating and nonrotating
missiles compared to the blast effect. If cumulative
blast effects were considered, the gap between thermal
and blast sure-kill and sure-safe regions would probably
be decreased even more. These results emphasize how
rotation reduces the dominance of the cumulative thermal
effect from nuclear weapons explosions.

Probability of Survival
and Maximum Temperature for
4-on-1 Attack

The previous results concerned the thermal threat

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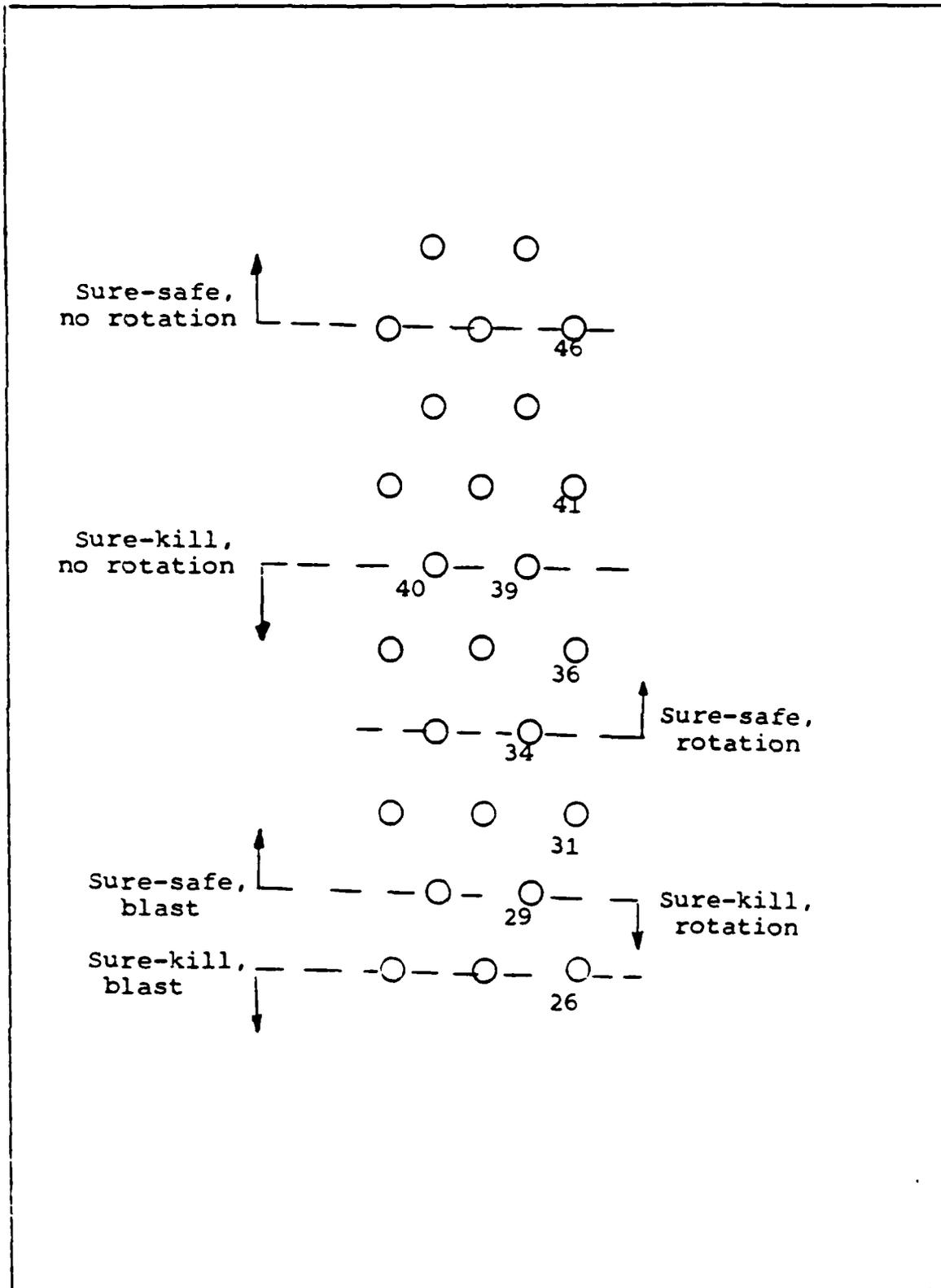
Fig. 11. Location of Sure-kill and Sure-Safe Regions

from a walk attack, where the bursts progress in an orderly fashion (for example, south to north). In the 4-on-1 attack, the missile was subjected to four bursts. The burst locations, relative to the launching missile, were such that the missile was radiated from all sides. The intent was to determine if the optimum rotation rate was scenario dependent. Each burst occurred every two seconds, and fell in a counterclockwise manner about the launching missile.

Figure 12 shows the probability of survival vs. rotation rate for a missile under a 4-on-1 attack. The probability of survival initially goes down, reaching a minimum at approximately .7 radians/sec. This occurs because the missile rotation rate, and the burst explosion rate are approximately the same. In otherwords, the missile was rotating into the thermal pulse as each weapon exploded. However, as the rotation rate increased, the probability of survival also increased. Thus, at the higher rotation rates, the thermal energy was effectively distributed on the missile surface, decreasing the maximum temperature, and increasing the probability of survival. Several other 4-on-1 scenarios were examined, and in all cases, the maximum rotation rate was the most effective.
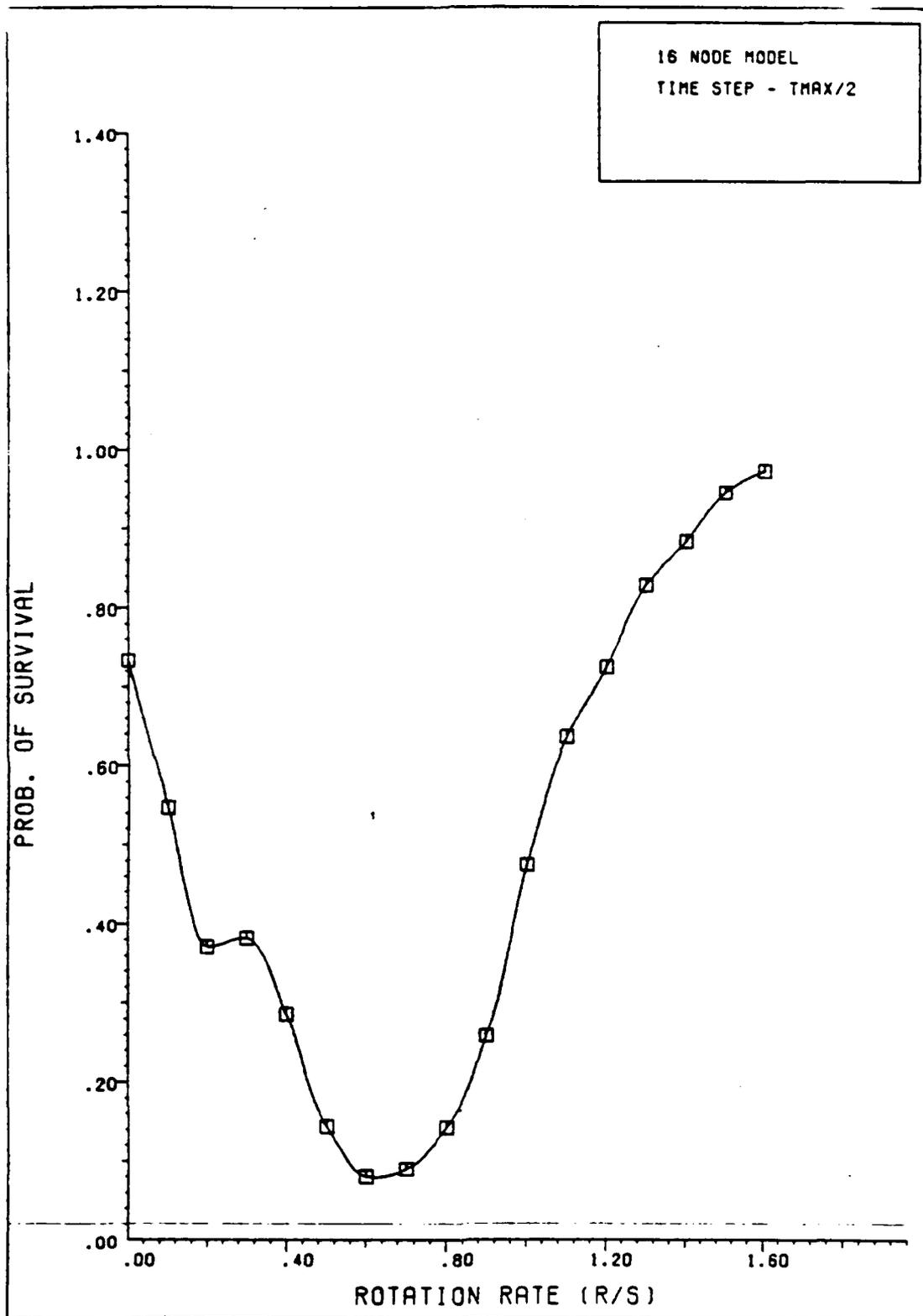
Fig. 12. Random Attack - Ps. vs. Rotation Rate

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Effect of Rotation on
Temperature for the Laser Threat

Figure 13 shows the maximum temperature versus rotation rate for the missile surface subjected to a laser pulse. The laser spot radius on target was 10 cm, with an intensity of 2000 J/cm^2-s.

The effect of rotation on maximum temperature is clearly shown for this scenario. As the rotation rate increases, the maximum temperature decreases to a minimum. The high temperatures at the low rotation rates are a result of the laser spot overlapping on the missile surface during the iteration process. As the rotation rate increases, the spot overlaps less until for each time step, the laser spot moves an entire spot width, and no overlapping occurs. As the rotation rate increases, and the temperature decreases, the probability of survival increases accordingly. Thus, for this limited scenario, rotation significantly increases the probability of survival. However, spot size drastically changes the rotation rate at which the minimum temperatures are reached.

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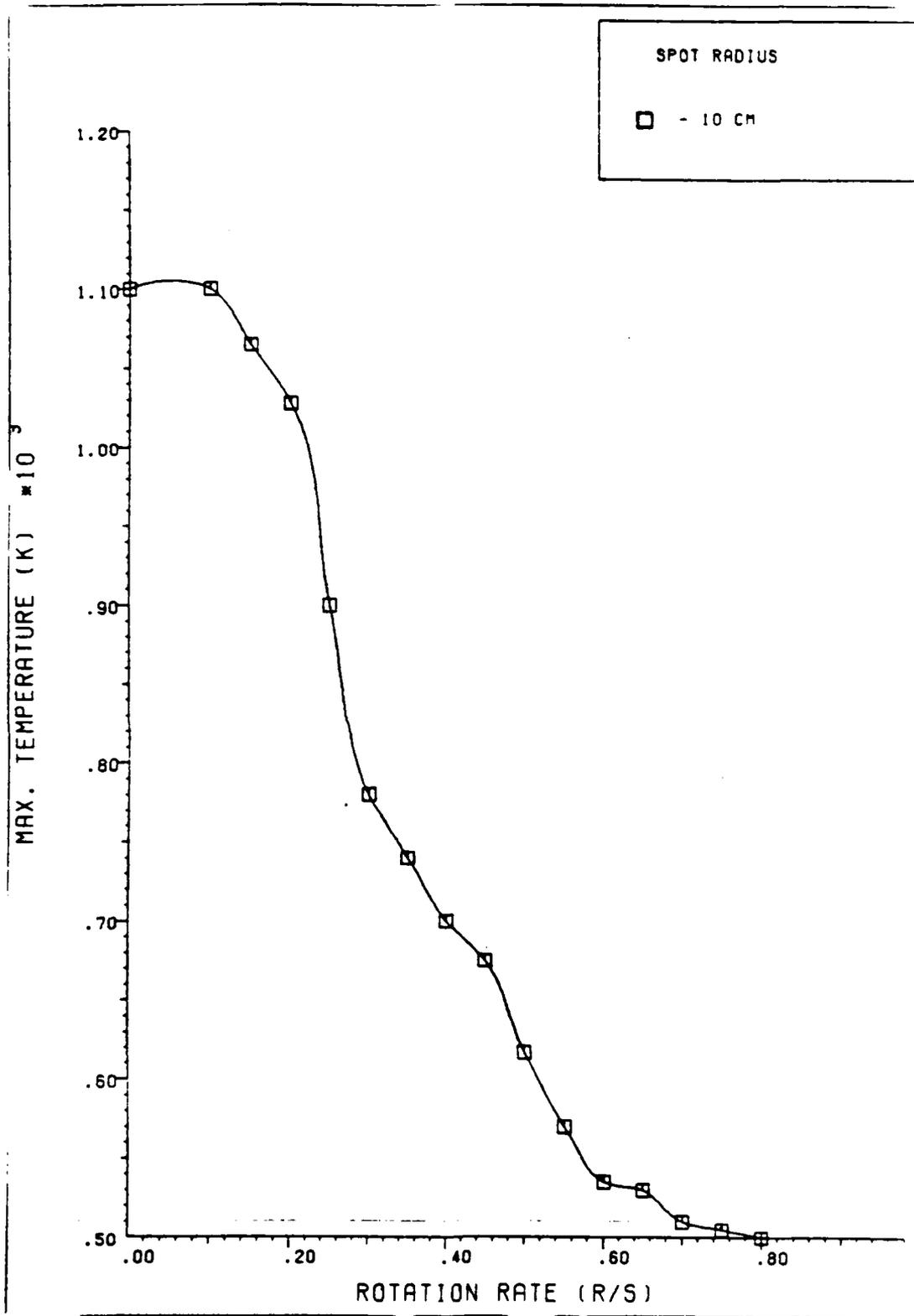
Fig. 13. Max Temperature vs. Rotation Rate - Laser

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Comparison of Spot Size
to Probability of Survival

Figure 14 shows the probabilty of survival versus rotation rate for a missile subjected to a one second laser pulse with an intensity of 2000 J/cm^2-s. The four curves are for the four spot sizes considered: 10, 20, 30, and 40 cm radius. The most obvious characteristic of the illustration is that as the spot size increases, the rotation rate required to cause an increase in survival also increases. This seems logical since a larger spot would require a higher rotation rate to reduce the spot overlap. For rotation rates restricted to 1.6 radians per second, a large spot could not be moved quickly enough to reduce the missile skin temperature. In that event, rotation would have little effect on the probability of survival for the missile.
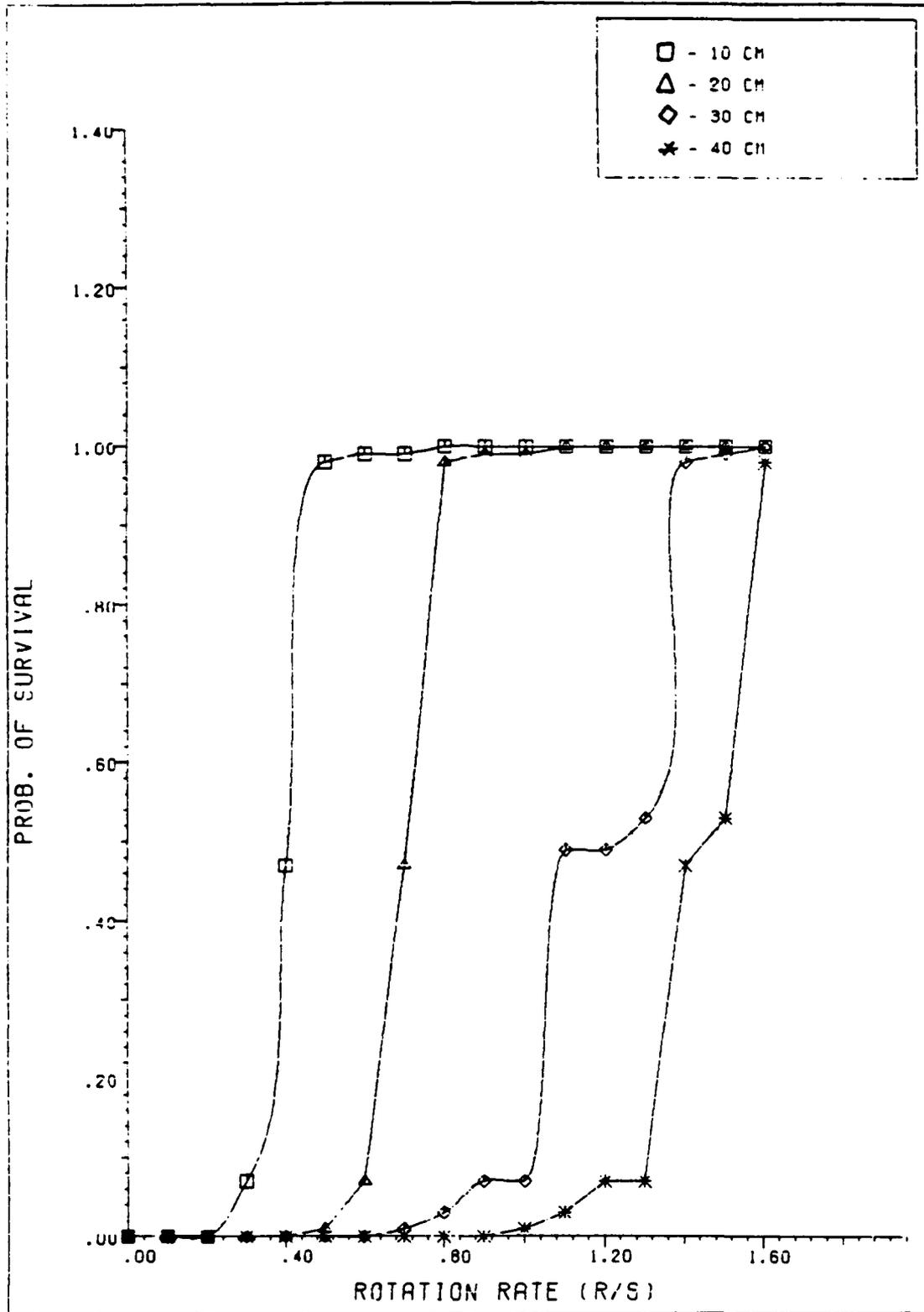
Fig. 14. Spot Comparison - Ps. vs. Rotation Rate

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Chapter V. <u>Conclusions</u> <u>and</u> <u>Recommendations</u>

<u>Conclusions</u>

From the results given in Chapter IV, the following
conclusions are made:

1. The maximum skin temperature for a missile
exposed to thermal radiation can be decreased if the
missile rotates. The most effective rotation rate
depends on the scenario. However, in general, the
faster the rotation rate, the greater decrease in skin
temperature. Therefore, rotation is an effective
defense against the thermal threat.

2. In a scenario such as a walk attack, where the
attack progresses from one quadrant (i.e. south to
north), rotation can have dramatic effects. In
particular, a relatively low optimum rotation rate of .8
radians/sec was observed. Using this optimum rotation
rate, the sure-kill region for the cumulative thermal
threat can be significantly decreased. Specifically,
for the walk attack scenario, 10 more missiles survive,
and the sure-kill region is reduced by approximately
2000 m.

3. For the 4-on-1 attack, where four bursts
surround a launching missile, rotation still
significantly decreases the maximum skin temperature.
However, the most effective rotation rate for this type

of attack was the maximum rate of 1.6 radians/sec.

4. As stated before, the cumulative thermal effect is more lethal than the noncumulative blast effect. However, when rotation is considered, the dominance of the thermal threat is decreased to a point where the sure-kill regions for the blast effect and the thermal effect are approximately the same.

5. Rotation is an effective defense against the laser energy threat. For the scenarios considered, the 1.6 radian/sec rotation rate was adequate to keep the missile skin maximum temperature below the sure-kill level. However, rotation as a defense against the laser threat does have certain limitations. A sufficiently powerful laser, with a large spot size could kill a missile before rotation could remove the missile surface from the spot. Therefore, for rotation to be effective, the threat against the missile must be known.

Recommendations

Based on the assumptions presented in Chapter I, as well as the observations made during the study, the following recommendations are made:

1. Since the effectiveness of rotation is scenario dependent, a more thorough investigation should be made into different scenario types.

2. A study should be made using the more accurate

cylindrical geometry between the missile surface and laser spot. This is especially true as the laser spot size increases to a point where the entire diameter of the missile is covered by the spot.

3. As recommended in a previous study by Hall, the synergistic effects of thermal heat and blast should be studied (Hall, 1985:66). This study did not investigate the mechanical stresses imposed on a rotating body. However, the increased load factor caused by rotation, coupled with the heat and blast from a nuclear explosion, may exceed the structural limits of the missile.

Appendix A.   Calculating the Rotation Correction Factor

This appendix outlines the method used to calculate
the rotation correction factor (RF). This correction
factor accounts for the cylindrical shape of the
missile. A correction factor was needed to determine
the amount of thermal radiation that falls incident
perpendicular to the missile skin's surface. An 8 node
model will be used for this illustration.

The Rotation Correction Factor

The RF was found by considering the geometry
between the burst point and the 8 nodes that make up the
missile's cylindrical shape. For this study, the RV's
were assumed to land directly on their targets, with no
aiming error. Thus, the burst locations are known
exactly. The next step was to find the exact location
of the 8 nodes.

Using a standard polar coordinate system, the
location of the 8 nodes was known for each time step by
their position vector, r, and angular displacement,
theta (θ). Since the missile radius is very small
compared to the distance between the burst and missile,
only the angular displacement was used. The next step
was to find the relative position where the thermal
radiation is perpendicular to the missile surface. This

position will also be identified by a relative angular displacement, called thetaprime. In order to find thetaprime, the burst-missile geometry must be known. Figure A-1 shows a burst-missile encounter. Since the missile flies straight north, it is convenient to define the angle beta as:

$$\text{Beta=arctangent}[\frac{(Y_{burst}-Y_{missile})}{X_{burst}-X_{missile}}] \qquad (A.1)$$

where
$Y_{missile}$ = missile's Y position, does not change
$X_{missile}$ = missile's X position
Y_{burst} = burst's Y position
X_{burst} = burst's X position

If the missile is north of the burst, the angle thetaprime can be found using the equation:

$$\text{Thetaprime} = (1.5*\pi) - \text{Beta} \qquad (A.2)$$

If the missile is south of the burst, the angle is found using the equation:

$$\text{Thetaprime} = (\pi/2) - \text{Beta} \qquad (A.3)$$

Thus, thetaprime is the relative angular location where the thermal radiation is perpendicular to the missile's skin. With the two angles theta, and

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Missile Position

$X_{missile}$, $Y_{missile}$

X (North)

Y
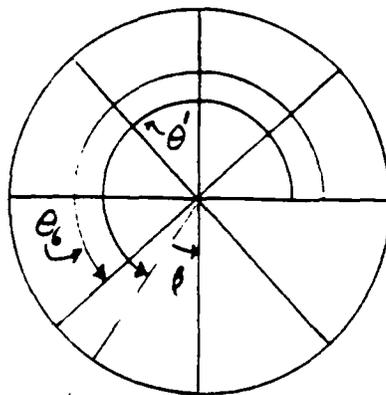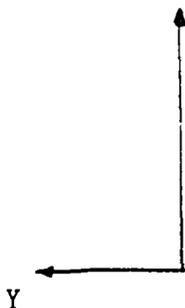
Burst Position

X_{burst}, Y_{burst}

(not to scale)

Figure A.1   Sample Burst-Missile Encounter

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thetaprime, the rotation correction factor for each node
can easily be determined. First, recognizing that the
cosine of the difference between thetaprime and the
angle theta for each node is the measure of the fraction
of the thermal radiation perpendicular to that node, the
RF for any node can be found using the following
equation:

$$RF(n) = Cos(Thetaprime-theta(n)) \qquad (A.4)$$

where

thetaprime = location on missile surface where
               radiation is perpendicular

theta(n) = location of node (n = 1,2,...8)

RF(n) = correction factor for node, n

For each time step, theta(n) changes, which in turn
changes the value of the correction factor RF(n). When
the difference between the two angles is greater than 90
degrees, the cosine becomes negative. This means the
radiation is shielded from the node, and therefore, the
RF(n) is set to zero. This of course assumes perfect
shielding, and does not account for scattering of the
radiation. However, radiation scattering was not
modelled in this study.

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Appendix B. <u>Skin</u> <u>Depth</u>, <u>and</u> <u>Absorption</u> <u>Coefficient</u>

This appendix shows sample calculations of skin depth and absorption coefficient for laser radiation on aluminum. The laser is assumed to be a chemical laser with an operating wavelength of $4.0 * 10^{-6}$ m. Further examples can be found in Bailey (Bailey, 1985: 42-44).

<u>Skin</u> <u>Depth</u>

Whenever electromagnetic radiation strikes a good conductor, like aluminum, it can be absorbed or reflected. In either case, the electromagnetic wave must penetrate the material in order to interact with the material's electrons. The depth of penetration can be found from:

$$= [\frac{\epsilon * c * \lambda}{\pi \; \sigma}]^{.5} \qquad (B.1)$$

where
$$\sigma = 3*10^7 \text{ mho/m}$$
$$\lambda = 4*10^{-6} \text{ m}$$
$$\epsilon = 9*10^{-12} \text{ } C^2/J\text{-m}$$
$$c = 3*10^8 \text{ m/sec}$$

Substituting into equation (B.1), skin depth is approximately $1.1*10^{-8}$ m. Thus, the heating is confined to the surface of the aluminum skin.

Absorption Coefficient

The fraction of energy actually absorbed by a material is known as the absorption coefficient. For good conductors, it is found using the equation:

$$\alpha = [\frac{4*\pi\,\delta}{\lambda}] \qquad\qquad (B.2)$$

Substituting into this equation, alpha is approximately .03. However, this calculation is based on an ideal material surface. The actual value is expected to be higher, because the missile surface has impurities, oxidation, and defects which would increase the energy coupling to the surface. Ready suggests a value of .1 (Ready,1971:49). Therefore, for this study, the absorption coefficient is .1 for all laser calculations.

Appendix C.   <u>Calculation</u> <u>of</u> <u>Minimum</u> <u>Energy</u> <u>Density</u>

The minimum energy density required to achieve a
thermal kill is calculated using the thin skin
approximation. Specifically, the amount of absorbed
thermal energy required to raise the missile skin
temperature above the sure-kill level of 809 degrees in
one second, is determined. Also, this calculation was
checked by two other methods. However, only the results
of these methods are presented, along with appropriate
references.

<u>Calculating</u> <u>Minimum</u>
<u>Energy</u> <u>Density</u>

As explained in chapter II, the missile skin
temperature can be found using the thin skin
approximation. The derivation leads to equation (2.2)
which is:

$$T_2 = \frac{[T_1(a - \frac{h \cdot \Delta T}{2}) + h\, T\, T_{air} + \alpha\, \Delta Q]}{(a + \frac{h \cdot T}{2})} \qquad (C.1)$$

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where

T_2 = temperature at end of jth time step (K)

T_1 = temperature at beginning of jth time step (K)

ΔT = time step, 1 second

T_{air} = temperature of ambient air (K)

$a = C_p \rho d$ (J/m^2-K)

h = convective heat transfer coeffient (J/m^2-s-K)

Q = absorbed thermal energy (J/m^2)

The missile's velocity and altitude are extremely high as it comes within range of the space based laser (Bailey, 1985). Under these conditions, the local convective heat transfer coeffient, h, will be very small. Using a procedure explained by Hall, h, can be calculated (Hall, 1985:85-87). For example, at 100 km altitude, and 3000 m/s velocity, h is approximately .04 J/m^2-s-K. Then using equation (C.1), and substituting in the appropriate values, the radiation absorption term, ΔQ, is approximately $1.5 * 10^6$ J/m^2.

This value was checked by two seperate methods. The first was taken from notes on laser weapons by Bailey (Bailey, 1985:45-46). This analysis determined the amount of energy needed to melt, or remove a depth of surface in a given amount of time. Neglecting loss process, and assuming all the energy goes into melting

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the material, the absorption term is approximately 3.0 * 10^6 J/m^2. The second method was taken from Raedy, and involves a two dimensional heat flow equation to calculate the temperature at any point and time in the laser spot (Raedy, 1971:75-85). This analysis also involved melting the material, and the calculated absorption term was approximately 2.75 * 10^6 J/m^2. Since complete melt through is not required to insure a kill, these two estimates are considered high. However, some melting surely occurs prior to failure, so for this study, the minimum absorbed energy density was assumed to be 2.0 * 10^6 J/m^2.

Appendix D. <u>Data</u> <u>for</u> <u>Figures</u> <u>in</u> <u>Chapter</u> <u>IV</u>

This appendix contains tables of data used to plot figures 7, 8, 12 and 14.

TABLE D-I

DATA USED TO PLOT FIGURE 7, MODEL COMPARISON
OF 8, 16, AND 32 MODELS
PROBABILITY OF SURVIVAL VS. ROTATION RATE

Omega	Model (nodes)		
(r/s)	8	16	32
0.0	.495	.495	.495
0.1	.728	.635	.618
0.2	.897	.897	.868
0.3	.994	.993	.991
0.4	.999	.999	.999
0.5	.999	.999	.999

Missile #41
Launch time: 0 sec
Time of first burst: 0 sec

TABLE D-II
DATA USED TO PLOT FIGURE 8

Omega (r/s)	MaxT (K)	Omega (r/s)	MaxT (K)
0.0	708	0.9	467
0.1	691	1.0	477
0.2	651	1.1	472
0.3	603	1.2	473
0.4	555	1.3	474
0.5	513	1.4	465
0.6	487	1.5	452
0.7	465	1.6	446
0.8	457		

Missile #41
Launch time: 0 sec
Time of first burst: 0 sec
Fireball rise considered

TABLE D-III
DATA FOR FIGURE 12
4-ON-1 RANDOM ATTACK

Omega (r/s)	Ps	Omega (r/s)	Ps
0.0	.733	0.9	.259
0.1	.547	1.0	.475
0.2	.371	1.1	.637
0.3	.382	1.2	.725
0.4	.286	1.3	.829
0.5	.144	1.4	.884
0.6	.080	1.5	.946
0.7	.090	1.6	.973
0.8	.143		

Missile #41
Launch time: 0 sec
Time of first burst: 0 sec

TABLE D-IV
DATA FOR FIGURE 14, SPOT SIZE COMPARISON
2000 J/CM^2, 10, 20, 30 AND 40 CM RADII

Omega (r/s)	Spot Size (cm)			
	10	20	30	40
0.0	0.00	0.00	0.00	0.00
0.1	0.00	0.00	0.00	0.00
0.2	0.00	0.00	0.00	0.00
0.3	0.07	0.00	0.00	0.00
0.4	0.47	0.00	0.00	0.00
0.5	0.98	0.01	0.00	0.00
0.6	0.99	0.07	0.00	0.00
0.7	0.99	0.47	0.01	0.00
0.8	1.00	0.98	0.03	0.00
0.9	1.00	0.99	0.07	0.01
1.0	1.00	0.99	0.07	0.03
1.1	1.00	1.00	0.49	0.07
1.2	1.00	1.00	0.53	0.07
1.3	1.00	1.00	0.98	0.27
1.4	1.00	1.00	0.99	0.47
1.5	1.00	1.00	1.00	0.53
1.6	1.00	1.00	1.00	0.98

Appendix E. Computer Program

This program is a modified version of a program called "Therm", written as part of a master's thesis by Lt. Barbara A. Hall. The program, Therm, was written in Fortran 77, and required a mainframe computer for effective operation. However, several simplifying conclusions were made by Lt. Hall, and incorporated in this program. Consequently, the following program is written in BASICA, an IBM, and Z-100 compatible Basic language. The program was run on Z-150 personal computer.

```
10  '*************************************************************
20  '****                                                    ****
30  '****         Cumulative Effect - With Rotation          ****
40  '****         Test Version #2, 16 node, T=TMAX/2         ****
45  '****              Program called 'T162'                ****
50  '****                                                    ****
60  '*************************************************************
70  '
80  '    *******************************************************
90  '    *                                                     *
100 '    *            DECLARE PROGRAM CONSTANTS                *
110 '    *                                                     *
120 '    *******************************************************
130 '
140              PI=3.14159:      REM     Radians
150              R=116.84:        REM     Radius of missile (cm)
160              THTA=0:          REM     Initial angular displacement
170              HOB=0:           REM     Height of burst (km)
180              ISS=619:         REM     Intensity  Sure-Safe  (Kelvin)
190              ISK=809:         REM     Intensity  Sure-Kill  (Kelvin)
200              CEP=200:         REM     Circular Error Probable (m)
210 '
220 '    *******************************************************
230 '
240 '    *******************************************************
250 '    *                                                     *
260 '    *          DECLARE MISSILE SKIN CONSTANTS             *
270 '    *                                                     *
280 '    *******************************************************
290 '
300              ALFA=.5:         REM     Absorptivity of Aluminum
310              CV=900:          REM     Specific Heat Capacity (J/Kg-K)
320              D=.001:          REM     Skin Thickness (m)
330              RHO=2700:        REM     Density of Aluminum (kg/m**3)
340 '
350 '    *******************************************************
360 '
370 '    *******************************************************
380 '    *                                                     *
390 '    *  DIMENSIONALIZE STORAGE ARRAYS FOR PROGRAM CALCULATION  *
400 '    *                                                     *
410 '    *******************************************************
420 '
430  DIM VDATA(52),ZDATA(52),XDATA(52),ANGDATA(72),SX(100),SY(100)
440  DIM DCT(6,32),HFB(6,32),VEL(32),ALT(32),DRD(32),ANG(32),H(32),TEMP(32)
450  DIM T2(16),DQ(16),RF(16),THETA(16),T1(16)
460 '
470 '    *******************************************************
480 '    *                                                     *
490 '    *       INITIALIZE ARRAYS WITH MISSILE FLIGHT DATA     *
500 '    *                                                     *
510 '    *******************************************************
520 '
530              GOSUB 4490
540 '
```

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```
550 '    *********************************************************************
560 '    *                                                                   *
570 '    *              INPUT ATTACK/WEAPON PARAMETERS                       *
580 '    *                                                                   *
590 '    *********************************************************************
600 '
610      FOR MN=41 TO 41
620      BLUE=0
630 '      INPUT "ENTER MISSILE NUMBER";MN
640 '      INPUT "ENTER DESIGNATED LAUNCH TIME";LT
650 '      INPUT "ENTER NUMBER OF WEAPON BURSTS AFFECTING MISSILE";MAXB
660 '      INPUT "ENTER TIME OF FIRST BURST ( >= launch time and even)";TB1
670 '      INPUT "ENTER YIELD (kt)";Y
680 '      INPUT "ENTER 1 IF YOU WANT FIREBALL RISE, 0 IF NOT";RISE
690 '      INPUT "ENTER ROTATION RATE OF MISSILE (in radians)";OMEGA
700      GOSUB 5300
710      OMEGA=BLUE/20
720 '    *********************************************************************
730 '
740 '    *********************************************************************
750 '    *                                                                   *
760 '    *         PRELIMINARY PROBABILITY DENSITY FUNCTION CALCULATIONS     *
770 '    *                                                                   *
780 '    *********************************************************************
790 '
800           BETA=(1!/4.108)*LOG(ISK/ISS)
810           ALPHA=.5*LOG(ISS*ISK)
820 '
830 '    *********************************************************************
840 '
850 '    *********************************************************************
860 '    *                                                                   *
870 '    *       PRELIMINARY MATH CALCULATIONS FOR THIS ITERATION            *
880 '    *                                                                   *
890 '    *********************************************************************
900 '
910           A=CV*RHO*D             :REM     (J/M**2-K)
920           TF=.18                 :REM     Thermal fraction
                                              (surface burst)
930           XM=5.5                 :REM     Critical point along
                                              missile length   (m)
940           TMAX=.0417*Y^.44       :REM     Thermal Maximum
950 '
960 '    *********************************************************************
970 '    *********************************************************************
980 '    *                                                                   *
990 '    *        BEGIN CALCULATIONS FOR THE MAXIMUM TEMPERATURE             *
1000 '   *                                                                   *
1010 '   *********************************************************************
1020 '   *                                                                   *
1030 '   *          CALCULATE INITIAL MISSILE CHARACTERISTICS               *
1040 '   *                                                                   *
1050 '   *********************************************************************
1060 '
1070             GOSUB 2340
1080 '
1090 '   *********************************************************************
```

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```
1100  '     *                                                                      *
111❄. '     *              CALCULATE FIREBALL CHARACTERISTICS                       *
11❄❄. '     *                                                                      *
1130  '     ****************************************************************************
1140  '
1150                        W=Y/1000
1160                        GOSUB 2620
1170  '
1180  '     ****************************************************************************
1190  '     ****************************************************************************
1200  '     *                                                                      *
1210  '     *       INITIALIZE MAX AND MIN TEMPERATURES FOR CALCULATIONS          *
1220  '     *                                                                      *
1230  '     ****************************************************************************
1240  '
1250                        LOWT=1000000!:   HIT=0!:   SUMPD=0!
1260  '
1270  '     ****************************************************************************
1280  '     ****************************************************************************
1290  '     *                                                                      *
1300  '     *          BEGIN ITERATION PROCESS FOR MAX TEMPERATURE                *
1310  '     *                                                                      *
1320  '     ****************************************************************************
1330  '
1340                        GOSUB 1630
1350  '
1360  '     ****************************************************************************
137❄. '     ****************************************************************************
138❄  '     *                                                                      *
1390  '     *                    PRINT THE RESULTS                                *
1400  '     *                                                                      *
1410  '     ****************************************************************************
1420  '
1430     LPRINT:PRINT
1440     LPRINT "MAX TEMPERATURE (kelvin)";MAXT
1450     LPRINT "MISSILE NUMBER";MN
1460     LPRINT "ROTATION RATE (radians)";OMEGA
1470     LPRINT "PROBABILITY OF SURVIVAL (Ps)";1-SUMPD
1480  '
1490  '     ****************************************************************************
1500  '     ****************************************************************************
1510  '     *                                                                      *
1520  '     *          TRY ANOTHER MISSILE/BURST SCENARIO OR QUIT                 *
1530  '     *                                                                      *
1540  '     ****************************************************************************
1550  BLUE=BLUE+1
1560  '         INPUT "WOULD YOU LIKE TO TRY ANOTHER SCENARIO (YES OR NO)?";TRY$
1570  IF BLUE <= 32 THEN GOTO 700 ELSE GOTO 1590
1580  '              IF TRY$="YES" THEN GOTO 600 ELSE END
1590  NEXT MN
1600  END
1610  '     ****************************************************************************
162❄. '     ****************************************************************************
16❄❄. '     ****************************************************************************
1640  '     *                                                                      *
1650  '     *                    SUBROUTINE: TCALC                                *
1660  '     *                                                                      *
1670  '     ****************************************************************************
```

```
16̲9̲0̲  '
1690 '
1700 NB=1
1710 J=0
1720 T1=TEMP(J)
1730 T2=T1+1!
1740 '
1742 FOR L=0 TO 15: T1(L)=TEMP(J): NEXT L
1750 '
1760    IF (T2 >= T1 AND J <= 20) THEN  GOTO 1770 ELSE GOTO 2170
1770       J=J+1
1780     COUNTER=J
1790        IF (NB < MAXB AND J*TMAX/2 >= 2*NB) THEN  GOTO 1800 ELSE GOTO 1830
1800             NB=NB+1
1810             NEWBST=1
1820                      GOTO 1860
1830             NEWBST=0
1840 '      END IF
1850 '
1860 FOR L=0 TO 15: DQ(L)=0: NEXT L
1870 '
1880        FOR K=1 TO NB
1890           TB=TB1+2*(K-1)
1900           SB=(TB+2)/2
1910 '
1920 '
1930        IF (NEWBST=1 AND K=NB) THEN  GOTO 1940 ELSE GOTO 1990
1940           T=TB1-LT+J*TMAX/2-(TB1+J*TMAX/2-TB)/2
1950                  GOSUB 3620
1960                  VEL=V:ALT=Z:DRD=X:ANG=PHI
1970                  GOSUB 3510
1980        GOTO 2020
1990 '      END IF
2000 '
2010                  GOSUB 3960
2020 '
2030 FOR L=0 TO 15
2040    DQ(L)=DQ(L)+DCT(K,J)*TF*Y*TAU*CF*RF(L)*4.186E+12/(4!*PI*(SR^2))
2050 '
2060 '
2070    T2(L)=(T1(L)*(A-H(J)*TMAX/4)+H(J)*TMAX/2*TEMP(J)+ALFA*DQ(L))/(A+H(J)*TMA
/4)
2080 '
2090 NEXT L
2100 GOSUB 5120
2110 NEXT K
2120 FOR L=0 TO 15
2130    IF T2(L) > T1(L) THEN T1(L)=T2(L)
2140 NEXT L
2150 T1=T2
2160 GOTO 1760
2170 MAXT=T1
2180 IF (MAXT < LOWT) THEN LOWT=MAXT
2190 IF (MAXT > HIT)  THEN HIT=MAXT
2200 '
```

```
2210 Z=(LOG(QMAXT)-ALPHA)/BETA
2220 ZP=ABS(Z)
2230 PZ=1!-1!/(2!*(1!+.196854*ZP+.115194*ZP^2+.000344*ZP^3+.019527*ZP^4)^4)
2240 '
2250 IF (Z >= 0!) THEN PDI=PZ ELSE PDI=1-PZ
2260 '
2270 '
2280 '
2290 SUMPD=SUMPD+PDI
2300 '
2310 '
2320 RETURN
2330 '*****************************************************************
2340 '    *****************************************************************
2350 '    *                                                              *
2360 '    *                    SUBROUTINE: INITCHAR                      *
2370 '    *                                                              *
2380 '    *****************************************************************
2390 J=0
2400 TO=TB1-LT
2410 T=TO
2420 GOSUB 3620
2430     VEL(J)=V:  ALT(J)=Z:  DRD(J)=X:  ANG(J)=PHI
2440 '
2450 '
2460 GOSUB 4160
2470     H(J)=H:  TEMP(J)=TA
2480 '
2490 'Calculate missile characteristics,h, and Temp for midpoint
2500 'of each time step
2510 '
2520 FOR J=1 TO 31
2530     TM=TO+(J-.5)*TMAX/2
2540     T=TM
2550         GOSUB 3620
2560           VEL(J)=V:  ALT(J)=Z:  DRD(J)=X:  ANG(J)=PHI
2570         GOSUB 4160
2580           H(J)=H:  TEMP(J)=TA
2590 '
2600 NEXT J
2610 RETURN
2620 ' *****************************************************************
2630 ' *                                                              *
2
```

```
 640 ' *                    SUBROUTINE: FIREBALLCALC                        *
2650 ' *                                                                     *
2660 ' *********************************************************************
2670 '
2680 FOR K=1 TO 4
2690     FOR J=1 TO 11
2700          DCT(K,J)=0!
2710          HFB(K,J)=0!
2720     NEXT J
2730 NEXT K
2740 J=0
2750 K=0
2760 NB=1
2770 '
2780 'FOR EACH TIME STEP J, FIND DIFFERENTIAL FLUENCE AND FIREBALL HEIGHT
2790 '
2800 FOR J=1 TO 31
2810     IF (NB < MAXB AND J*TMAX/2 >= 2*NB) THEN  GOTO 2320 ELSE GOTO 2850
2820          NB=NB+1
2830          NEWBST=1
2840     GOTO 2860
2850          NEWBST=0
2860 '
2870 '
2880 '
2890 'FOR EACH BURST K THAT HAS OCCURED, FIND THE THERMAL FLUENCE
2900 '
2910 FOR K=1 TO NB
2920     TB=TB1+2*(K-1)
2930       TP=(TB1+J*TMAX/2-TB)/TMAX
2940          IF (TP <= 10) THEN GOTO 2950 ELSE GOTO 3070
2950             GOSUB 3240:    CTU=CT
2960             TP=TP-.5
2970 '
2980             IF (TP > 0) THEN  GOTO 2990 ELSE GOTO 3020
2990             GOSUB 3240:  CTD=CT
3000 '
3010             GOTO 3050
3020               CTD=0!
3030 '
3040 '
3050 DCT(K,J)=CTU-CTD
3060 '
3070 '
3080 'Find fireball rise for burst k at time t
3090 '
3100 IF (RISE = 1) THEN  GOTO 3110 ELSE GOTO 3200
3110     IF (NEWBST=1 AND K=NB) THEN GOTO 3120 ELSE GOTO 3140
3120        T=(TB1+J*TMAX/2-TB)/2!
3130     GOTO 3170
3140        T=TB1+(J-.5)*TMAX/2-TB
3150 '
3160 '
3170 HFB(K,J)=21640.8*(W^.177)*(1!-(1!-T/240!)^2)
```

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```
3090 '
3100 '
3200 NEXT K
3210 NEXT J
3220 '
3230 RETURN
3240 '**********************************************************************
3250 '
3260 '   *                       SUBROUTINE: THERMCOEF                      *
3270 '   *                                                                  *
3280 '   **********************************************************************
3290 '
3300 IF (TP <= .75) THEN CT=-.02*TP+.24*(TP^2)
3310 '
3320 IF (TP > .75 AND TP <= 1.5) THEN CT=.32*TP-.12
3330 '
3340 IF (TP > 1.5 AND TP <= 2.5) THEN CT=-.257219+.556415*TP-.0969029*(TP^2)
3350 '
3360 IF (TP > 2.5 AND TP < 10) THEN CT=.335808+.0949904*TP-4.94514E-03*(TP^2)
3370 '
3380 IF TP>=10 THEN CT=.8
3390 '
3400 '
3410 RETURN
3420 '   **********************************************************************
3430 '   *                                                                  *
3440 '   *                 SUBROUTINE:  ALTMISSPOSN                         *
3450 '   *       Used if burst occurs during time step, and new missile    *
3460 '   *       position characteristics required. If not, gosub 5760.     *
3470 '   *                                                                  *
3480 '   **********************************************************************
3490 '
3500 '
3510 DELTAZ=ALT-HFB(K,J)
3520 XB=SX(SB):   YB=SY(SB)
3530    GR=SQR((SY(MN)-YB)^2+(DRD-XB)^2)
3540    SR=SQR(GR^2+DELTAZ^2):   SRX=DRD-XB:   SRZ=DELTAZ
3550       IF VEL=0 THEN GOTO 3560 ELSE GOTO 3570
3560          CF=1:   GOTO 3590
3570       COSPHI=(SRX*VEL*COS(PHI)+SRZ*VEL*SIN(PHI))/(SR*VEL)
3580          CF=SQR(1!-COSPHI^2)
3590    TAU=EXP(-.02455-6.439E-05*SR-1.407E-09*SR^2+1.792E-14*SR^3)
3600 GOSUB 4860:COUNTER=COUNTER+1
3610 RETURN
3620 '   **********************************************************************
```

```
3630 '  *                                                                    *
3640 '  *              SUBROUTINE: MISSILECALC                                *
3650 '  *                                                                    *
3660 '  **********************************************************************
3670 '
3680      TD=INT(T):  TU=TD+1:      REM   UPPER AND LOWER INTEGER VALUE OF T
3690 '
3700          IF T>50 THEN GOTO 3710 ELSE GOTO 3780
3710 '
3720              V=105!*T-1350
3730              Z=2460!*T-65000!
3740              X=3700!*T-127000!
3750 '
3760          GOTO 3820
3770 '
3780              V=(T-TD)*(VDATA(TU+1)-VDATA(TD+1))+VDATA(TD+1)
3790              Z=(T-TD)*(ZDATA(TU+1)-ZDATA(TD+1))+ZDATA(TD+1)
3800              X=(T-TD)*(XDATA(TU+1)-XDATA(TD+1))+XDATA(TD+1)
3810 '
3820 '
3830      IF (T > 70) THEN  GOTO 3840 ELSE GOTO 3860
3840          PHI=30.6-.1*(T-70)
3850      GOTO 3880
3860          PHI=(T-TD)*(ANGDATA(TU+1)-ANGDATA(TD+1))+ANGDATA(TD+1)
3870 '
3880              V=V*.3048
3890              Z=Z*.3048
3900              X=X*.3048+SX(MN)
3910              PHI=PHI*PI/180
3920 RETURN
3930 '
3940 '  **********************************************************************
3950 '  *                                                                    *
3960 '  *              SUBROUTINE: MISSPOSN                                   *
3970 '  *                                                                    *
3980 '  **********************************************************************
3990 '
4000          DELTAZ=ALT(J)-HFB(K,J)
4010              XB=SX(SB): YB=SY(SB)
4020              GR=SQR((SY(MN)-YB)^2+(DRD(J)-XB)^2)
4030              SR=SQR(GR^2+DELTAZ^2): SRX=DRD(J)-XB: SRZ=DELTAZ
4040 '
4050          IF VEL(J)=0 THEN GOTO 4060 ELSE GOTO 4070
4060              CF=1: GOTO 4090
4070          COSPHI=(SRX*VEL(J)*COS(ANG(J))+SRZ*VEL(J)*SIN(ANG(J)))/(SR*VEL(J))
4080              CF=SQR(1!-COSPHI^2)
4090          TAU=EXP(-.02455-6.439E-05*SR-1.407E-09*SR^2+1.792E-14*SR^3)
4100 DRD=DRD(J): GOSUB 4860:COUNTER=COUNTER+1
4110 RETURN
4120 '  **********************************************************************
4130 '
4140 '
4150 '  **********************************************************************
4160 '  *                                                                    *
4170 '  *          SUBROUTINE: HEATCALC (heat transfer coefficient h (j/m2-s-k)   *
```

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```
4160 ' *
4190 ' *******************************************************************
4200 '
4210              Z=ALT(J): GOSUB 4310: REM Find ambient air parameters
4220              CP=240*4.184
4230              RE=RHOA*VEL(J)*XM/MU
4240              PR=MU*CP/KA
4250    IF RE<=500000! THEN NU=.332*PR^.333*RE^.5 ELSE NU=.0296*PR^.333*RE^.8
4260    H=NU*KA/XM
4270 RETURN
4280 '
4290 ' *******************************************************************
4300 ' *                                                               *
4310 ' *          SUBROUTINE: U.S. Standard Atmospheres  ( 47 km )     *
4320 ' *                                                               *
4330 ' *******************************************************************
4340 '
4350 IF Z<11000 THEN LK=-.006545: PK=101300!: TK=288.15:ZK=0!
4360 IF Z>=11000 AND Z<20000 THEN LK=0!: PK=22690!: TK=216.65: ZK=11000
4370 IF Z>=20000 AND Z<32000 THEN LK=.001: PK=5528!: TK=216.65: ZK=20000
4380 IF Z>=32000 AND Z<47000! THEN LK=.0028: PK=888.8: TK=228.65: ZK=32000
4390 IF Z>47000! THEN PRINT" Consult NOAA for values"
4400 IF LK=0 THEN GOTO 4410 ELSE GOTO 4420
4410     P=PK*EXP(-.034164*(Z-ZK)/TK): TA=TK: GOTO 4430
4420     TA=TK+LK*(Z-ZK): P=PK*(TK/TA)^(.034164/LK): GOTO 4430
4430 RHOA=.003484*P/TA
4440 MU=(1.458E-06*TA^1.5)/(TA+110.4):   REM (kg/m-s)
4450 KA=(2.64638E-03*TA^1.5)/(TA+245.4*10^(-12!/TA)):   REM (j/m-s-k)
4460 '
4470 RETURN
4480 '
4490 ' *******************************************************************
4500 ' *                                                               *
4510 ' *              SUBROUTINE: INITIAL DATA INPUT                   *
4520 ' *                                                               *
4530 ' *******************************************************************
4540 '
4550 OPEN "I",#1,"veldata.txt"
4560 FOR I=1 TO 51: INPUT #1,VDATA(I): NEXT I : CLOSE #1
4570 OPEN "I",#1,"altdata.txt"
4580 FOR I=1 TO 51: INPUT #1,ZDATA(I): NEXT I : CLOSE #1
4590 OPEN "I",#3,"drddata.txt"
4600 FOR I=1 TO 51: INPUT #3,XDATA(I): NEXT I : CLOSE #3
4610 OPEN "I",#1,"degdata.txt"
4620 FOR I=1 TO 71: INPUT #1,ANGDATA(I): NEXT I:CLOSE #1
4630 'OPEN "I",#1,"SILO.txt"
4640 'FOR I=1 TO 100: INPUT #1,MLT(I):  NEXT I : CLOSE #1
4650 '
4660 ' *******************************************************************
4670 ' *                                                               *
4680 ' *              SILO POSITIONS (X & Y COORDINATES)               *
4690 ' *                                                               *
4700 ' *******************************************************************
```

```
4710 '
47??  DX=519.62 : DY=300
4730     FOR I=0 TO 95 STEP 5
4740        SY(I+1)=0:  SY(I+2)=2*DY: SY(I+3)=4*DY: SY(I+4)=DY: SY(I+5)=3*DY
4750     NEXT I
4760 '
4770 J=0
4780     FOR I=0 TO 38 STEP 2
4790     SX(J+1)=I*DX:SX(J+2)=I*DX:SX(J+3)=I*DX:SX(J+4)=(I+1)*DX:SX(J+5)=(I+1)*DX
4800     J=J+5
4810   NEXT I
4820 RETURN
4830 ' ***************************************************************************
4840 ' ***************************************************************************
4850 ' *                                                                        *
4360 ' *                    ROTATION FACTOR CALCULATIONS                        *
4370 ' *                                                                        *
4880 ' ***************************************************************************
4890 '
4900 IF J=COUNTER THEN GOTO 4910 ELSE GOTO 4960
4910 THETA(0)=THTA+THETA(0)
4920     FOR I=1 TO 15
4930        THETA(I)=THETA(I-1)+PI*.125
4940     NEXT I
4950 '
4960       BOTTOM=DRD-XB: TOP=SY(MN)-YB
4970       IF BOTTOM=0 THEN GAMMA=0    ELSE GAMMA=ATN(TOP/BOTTOM)
49?? '
4990 '
5000     FOR I=0 TO 15
5010 '
5020     IF DRD(J) > XB THEN THETAPRIME=(1.5*PI)+GAMMA
5022     IF DRD(J) <= XB THEN THETAPRIME=(.5*PI)+GAMMA
5030         ZPRIME=ABS(THETAPRIME-THETA(I))
5040         RF(I)=COS(ZPRIME)
5050              IF RF(I)<.25 THEN RF(I)=.25
5060         THTA=OMEGA*TMAX/2
5070     NEXT I
5080 '
5090 RETURN
5100 ' *                                                                        *
5110 ' ***************************************************************************
```

```
5120 ' *                                                              *
5130 ' *                     PRINT THE RESULTS                         *
5140 ' *                                                              *
5150 ' ***********************************************************************
5160 ' *                                                              *
5170 'LPRINT "TIME STEP";J,    "BURST NUMBER";K,"T/TMAX";((J-.5)*TMAX/2)/TMAX
5180 'LPRINT "NODE      TEMP           THETA          ROTATE-FACTOR          GAMMA"
5190 FOR I=0 TO 15
5200 '
5210 IF T2(I) > T2 THEN T2=T2(I)
5220 'LPRINT USING "###";I+1,
5230 'LPRINT USING "  ####.##";T2(I),
5240 'LPRINT USING "          ####.###";THETA(I)*180/PI,
5250 'LPRINT USING "          ##.####";RF(I),
5260 'LPRINT USING "          ###.###";GAMMA*180/PI
5270 NEXT I
5280 '
5290 RETURN
5300 '
5310 LT=0
5320 TB1=0:    MAXB=4
5330 Y=2000: RISE=1
5340 THTA=0
5350 FOR I=0 TO 15: THETA(I)=0: NEXT I
5360 RETURN
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Vita

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Survivability studies have shown that intercontinental ballistic missiles are vulnerable to thermal effects. In particular, the cumulative thermal effect from a multiburst attack, and laser thermal energy can seriously damage or destroy a missile. One possible defense against the thermal threat is rotation of the missile. The purpose of this thesis was to determine if rotation decreased the maximum skin temperature of the missile, increasing the missile's probability of survival.

The study investigated several different scenarios. The first scenario was the Peacekeeper Dense Pack missile system. The missile field was subjected to a walk attack of 2 MT weapons, with the incoming RV's exploding every two seconds. The second scenario was a 4-on-1 attack of a missile launching system. More specifically, one missile was subjected to four bursts located in various positions surrounding the missile. The intent was to determine if rotating a missile, even when surrounded by thermal radiation, would increase the probability of survival. Finally, the missile is attacked by a space-based laser with a maximum absolute power of 10 megawatts. In all cases, the rotation rate was limited to a maximum of 1.6 radians/second, as established by studies at the Air Force Institue of Technology. Using computer programs, the maximum skin temperature was calculated, with the resultant probability of damage determined using a cumulative log-normal distribution function. Comparisons were made between the rotating and nonrotating missiles to determine if rotation did increase the probability of survival for the missile system.

In all scenarios studied, rotation significantly decreased the maximum skin temperature, increasing the probability of survival for the missile. The decrease was most dramatic for the walk attack, where an optimum rotation rate of .8 radians/second was established. For the 4-on-1 attack, rotation was effective, but required the maximum 1.6 radians/second rotation rate for best results. Finally, for the laser threat, rotation was effective for the scenarios studied, with the maximum rotation rate providing the greatest amount of protection. As a consequence, even at these relatively low rotation rates, rotation is an effective defense against the thermal threat.

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